Systematic Review Article

External apical root resorption assessment revisited: a scoping review

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ABSTRACT

Objectives: To provide a comprehensive critique of the diagnosis of root resorption using panoramic and periapical radiography, including discussion of the various methods of measurement, severity spectrum, and to shed light on a significant factor predisposing to resorption: treatment duration.

Materials and Methods: The articles reviewed involved human subjects undergoing buccal fixed orthodontic treatment, diagnosed by panoramic or intraoral radiographs at the beginning and end of treatment. Treatment duration and external apical root resorption (EARR) had to be recorded to be included in the study. Relevant sources were searched using various platforms including PubMed, Scopus, and WoS. All sources of evidence, regardless of language, were included in the study.

Results: The search strategy yielded 704 studies; screening by title and abstract yielded 389 articles for full-text review. Forty studies were finally included and categorized according to the type of radiograph used to diagnose EARR: authors of 18 studies used panoramic radiographs, and authors of 22 studies used intraoral radiographs.

Conclusions: In this study, we revealed a lack of agreement among authors concerning the diagnosis and measurement methods of external apical root resorption, resulting in inconsistencies in the results. Additionally, patient- and treatment-related factors, including treatment duration, were found to be inconsistently associated with the development of EARR. Standardization of diagnostic protocols and refinement of measurement techniques are essential to improve the accuracy of orthodontic care. (*Angle Orthod*. 0000;00:000–000.)

KEY WORDS: Root resorption; Orthodontic treatment; Fixed appliance; Treatment duration; Measurement method; Scopus review

INTRODUCTION

In daily orthodontic practice, root resorption continues to be a complex, significant challenge.[1] Over the years, a good deal of research has been devoted to this topic[2–4] of critical medical and legal importance in orthodontics. Nevertheless, still no consensus exists on the optimal diagnostic method for this pathology or on the most effective approach to measure its severity.[5]

In the orthodontic literature, various methods of assessing root resorption have been explored, ranging from traditional diagnostic radiography to three-dimensional (3D) methods using cone-beam computed tomography (CBCT).[6] Nevertheless, lateral, panoramic, and periapical radiographs are still the types most commonly used for orthodontic diagnostics in everyday clinical practice.[7,8]

In a historical review of the literature, a variety of measurement methodologies have been used to diagnose and assess the severity of root resorption, ranging from elementary techniques[9] to more sophisticated methods involving complicated mathematical formulas,[10] or even software analysis.[11] Other methods[12,13] provide a nuanced classification of the severity of external apical root resorption (EARR) based on a perceptual assessment of the apex by an observer. These measurement methods are important in determining and classifying the extent of EARR in the individual patient, as they elucidate

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Accepted: May 4, 2025. Submitted: September 10, 2024.
Published Online: July 11, 2025

the specific risk factors for as well as those that protect against the occurrence, severity, and development of EARR.

Several patient-related factors, such as age,[6] malocclusion,[14] and genetic predisposition,[15] have been associated with EARR, with some degree of conflicting results. Treatment duration has been identified in several meta-analyses as a significant treatment-related predisposing factor associated with EARR occurrence and severity.[6,16] However, substantial variability exists among studies regarding its impact, likely due to differences in methodology, measurement techniques, and sample characteristics.[17]

The complexities of diagnosing and measuring EARR present a significant challenge in making sense of the best scientific evidence currently available in orthodontics. The uncertainty regarding the influence of EARR diagnostic processes on associated risk-factor predictors highlights critical knowledge gaps. The aim of this paper was to conduct and provide a comprehensive scoping review of EARR diagnoses made using panoramic and periapical radiographs, the two methods most commonly used in clinical practice. Secondary aims included enhancing understanding and informing clinical practice by critically evaluating the measurement methods used, the severity spectrum, and the influence of different approaches on the association with treatment duration.

MATERIALS AND METHODS

Protocols and Guidelines

In this review, we adhered to the guidelines outlined in the *JBI Evidence Synthesis Template and Manual* (Peters et al., 2020[18]) as well as the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) extension designed for scoping reviews (Tricco et al.[19]).

Review Questions

A participant, concept, context (PCC) question was proposed to select eligible studies: "Is the literature consistent regarding the radiographic diagnostic method, measurement, and severity scale of external apical root resorption during orthodontic treatment with fixed appliances?"

Inclusion Criteria

Participants. The review included human subjects undergoing their first orthodontic treatment with fixed appliances, without adjunct therapies, systemic/periodontal diseases, or medications affecting oral health. Exclusion criteria included a history of dental trauma or root canal treatment of upper incisors. EARR diagnosis in at least one upper incisor was required, measured by periapical/panoramic radiographs, with recorded treatment duration.

Concept. In the study, diagnostic methods were critically evaluated using panoramic and periapical radiographs, examining severity and treatment duration as a key factor for resorption.

Context. Global evidence from various sources was accepted.

Types of sources of evidence. In vitro studies, animal research, histological studies, reviews, and opinion pieces were excluded. No restrictions on study duration or language were imposed if the PCC criteria were met.

Search Strategy

The search strategy focused on the concept of root resorption in the context of orthodontic treatment. Relevant sources were searched using different platforms, including PubMed, Scopus, and WoS. Selected studies that met the inclusion criteria were then carefully reviewed. The authors of the primary literature were contacted directly when necessary, and all sources of evidence, regardless of language, were considered for inclusion. Details of the search methodology, including relevant keywords and index terms tailored to each database consulted are provided in Appendix 1.

Source of Evidence Screening and Selection

The screening process followed a rigorous and structured approach and was divided into four steps: (1) removal of duplicates,[20] (2) review of title, (3) review of abstract, and (4) review of full-text. This was carried out independently by two researchers (P.I.D. and A.O.P.), ensuring an unbiased selection process. Disagreements were resolved by consensus or by a third reviewer (A.I.L.).

Data Extraction

Data extraction was conducted by one reviewer (P.I.D.) and verified by a second reviewer (A.O.P.). Data were divided into two categories: panoramic versus periapical radiographs, further subdivided by measurement method and whether EARR results were reported in percentages or millimeters. The variables recorded are described in Tables 1 and 2.[3,4,8,9,11,13,21–56]

Analysis and Presentation of Results

A table was created to extract data from the different studies. In cases where only one group met the inclusion criteria, the article was included, presenting only the calculated sample size and data for that group.

Table 1. Characteristics of Included Studies That Used Panoramic Radiography for the Diagnosis of External Apical Root Resorption (EARR)[a]

Author (Year)	Location	Sample Size, Upper Incisors Roots Measured	Sample Size, Patients	Treatment Duration, mo	EARR Measurement Method	EARR Measurement Programm
Alexander (1996)[40]	Stony Brook, NY, USA	112	56	Range, 22–27	Sharpe et al.[13] (scale)	Visual, Sharpe
Nigul et al. (2006)[48]	Tartu, Estonia	281	75	Range, 4–38	Linge and Linge[3] (mm)	NR
Pandis et al. (2008)[50]	Athens, Greece.	384	96	26.43 ± 6.29	Correction facctor: Assessment of the magnification of the maxillary incisors in panoramic radiographs was performed by inclusion of a graded tip of a periodontal probe in the panoramic radiographs. The metal tip was temporarily bonded between the maxillary central incisors from the incisal edge and upward (mm).	With a 3 × magnifying glass and a fine-tip digital caliper with accuracy up to 0.01 mm (Mitutoyo Digimatic NTD12-6"C, Mitutoyo, Kanagawa, Japan) interfaced with an Excel spreadsheet (Microsoft, Redmond, Wash).
Iglesias-Linares et al. (2012)[43]	Seville, Spain	54	54	31.1 ± 6.4	Linge and Linge[3] modified by Brezniak et al.[10] (mm)	Nemoceph Dental Studio
Llamas-Carreras et al. (2012)[47]	Seville, Spain	38	38	24.0 ± 12.0	CF: To allow intrapatient standardization, root resorptions in the root filled tooth (RRE) and contralateral tooth with vital pulp (RRV) were calculated. Then the proportion of root resorption (PRR) for each patient was calculated as follows: PRR = RRE/RRV (mm).	Adobe Photoshop CS® software
Rakhshan et al. (2012)[52]	Tehran, Iran	451	132	28.54 ± 9.71	Linge and Linge[3] (mm)	NR
Linhartova et al. (2013)[46]	Brno, Czech Republic	424	106	34.5 ± 15.6	Linge and Linge[3] modified by Brezniak et al.[10] (mm)	NR
Iglesias-Linares et al. (2014)[44]	Seville, Spain	87	87	27.5 ± 8.3	Linge and Linge[3] modified by Brezniak et al.[10] (mm)	NR
Jacobs et al. (2014)[45]	Mainz, Germany	852	213	19.8 ± 5.2	Linge and Linge[3] modified by Brezniak et al.[10] (%)	NR
Pereira et al. (2014)[51]	Coimbra, Portugal	195	195	36 ± 10	Linge and Linge[3] modified by Brezniak et al.[10] (%)	Apical Resorption Image Analysis System (ARIAS), Porto, Portugal. MATLAB version 7.12.0.635 (R2011a, MathWorks company, Natick, Mass, USA)
Savoldi et al. (2015)[53]	Brescia, Italy	156	93	25.2	CF: For each film, the length of the mesiodistal diameter of the crown of the mandibular right first molar was measured in pixels, and then all the measurements were converted using this value as the specific unit for each patient.	Adobe Photoshop CS6®
Yi et al. (2018)[54]	Chengdu, China	11: 40; 12: 40; 21: 40; 22: 40; total: 160	40	20.83 ± 5.29	Linge and Linge[3] modified by Brezniak et al.[10] (%)	Marosis Enterprise PACS; Infinitt Healthcare, Seoul, Korea
Qin et al. (2019)[4]	Wenzhou, Zhejiang, China	98	98	21.17 ± 5.13	Linge and Linge[3] modified by Brezniak et al.[10] (mm)	NR
Pamukçu et al. (2020)[49]	Ankara, Türkiye	11: 30; 12: 30; 21: 30; 22: 30; total: 120	30	26.87 ± 7.67	Fritz et al.[55]; Gay et al.[56] (2017), (%)	ImageJ (US National Institutes of Health, Bethesda, Md, USA).
Ciurla et al. (2021)[42]	Lublin, Poland	404	101	31.1 ± 6.4	Linge and Linge[3] modified by Brezniak et al.[10] (%)	Planmeca Romexis Viewer software
Lee et al. (2022)[11]	Seoul, South Korea	118	118	33.6 ± 8.3	Linge and Linge[3] modified by Brezniak et al.[10] (mm)	Cranex31 system (Soredex, Helsinki, Finland); ZeTTA PACS Viewer
Baghaei et al. (2023)[41]	Birmingham, Ala, USA	780	195	19.4 ± 6.4	CF: We used the ruler on the cephalometric radiograph to measure the molar crown width and transferred that measurement to calibrate the panoramic radiographs (%).	Dolphin Imaging software (Chatsworth, Calif, USA)
Kaya et al. (2023)[8]	Bahcelievler-Ankara, Türkiye	412	103	27.21 ± 7.63	Malmgren et al.[12]	Visual; Malmgren

[a] CF indicates correction factor; NR, Not reported; rRCR, Relative changes of root to crown ratio.

Table 1. Extended

Rx Parameters	EARR Definition and Severity	Mean EARR Founded	Severity of EARR, %	Prevalence of EARR
The same Ritter Midwest Panoral (Des Plaines, Ill) and Gendex GX900 (Gendex, Milwaukee, Wis) machines were used to obtain the panoramic and occlusal films.	Sharpe	Mean score scale of Sharpe: Maxilla central incisors: 0.28 ± 0.07; lateral central incisors: 0.37 ± 0.9; total: 0.32 ± 0.5	NR	22.00%
Different x-ray machines were used to obtain the panoramic radiographs; the position of the patient was not standardized.	Sharpe	12: 1.57 ± 1.2 mm; 11: 1.61 ± 1.27 mm; 21: 1.48 ± 1.05 mm; 22: 1.35 ± 1.02 mm; total: 1.50 ± 1.13 mm	Scale of Sharpe: 0: 12%; 1: 64%; 2: 14.6%; 3: 2.6%; Missing: 6.6.%	88.00%
NR	NR	11: 1.29 ± 1.03 mm; 12: 1.44 ± 1.11 mm; 21: 1.17 ± 1.11 mm; 22: 1.29 ± 1.21 mm; total: 1.29 ± 1.11 mm	NR	NR
NR	EARR > 2 mm; no EARR < 2 mm	EARR group: 3.12 ± 0.71 mm; no EARR group: 1.06 ± 0.5 mm; total: 2.09 ± 0.6 mm	NR	EARR > 2 mm: (n: 25) 46%; EARR < 2 mm: (n: 29) 54%
Promax®, Planmeca, class 1, type B, 80 KHz, Planmeca, Helsinki, Finland	NR	1.1 ± 1.0 mm	NR	NR
Same panoramic unit (Odontorama PC, Trophy Radiologie, Marne La Valle, France) + Other unknown units	EARR = root pretreatment – (root posttreatment ×CF). The percentage changes in the root lengths were calculated using Copeland and Green's criteria, EARR ≥ 1.20 mm was regarded as clinical EARR.	1.377 ± 1.214 mm	NR	Central incisor: 32.9%; lateral incisor: 58.3%
NR	EARR > 2 mm; no EARR < 2 mm	EARR group: 2.31 ± 0.47 mm; no EARR group: 0.51 ± 0.5 mm; total: 1.41 ± 0.97 mm	NR	EARR > 2 mm: (n: 74) 70%; EARR < 2 mm: (n: 32) 30%
NR	EARR > 2 mm; no EARR < 2 mm	NR	EARR > 2 mm: (n: 37) 42%; EARR < 2 mm: (n: 50) 58%	EARR > 2 mm: (n: 37) 42%; EARR < 2 mm: (n: 50) 58%
NR	Malmgren	NR	Teeth affected by severe EARR: 12,22: 1 (0.2%); 11,21: 1 (0.2%)	NR
Both radiographs were performed with the same equipment.	NR	12: 11 ± 0.9%; 11: 10 ± 0.8%; 21: 10 ± 1%; 22: 10 ± 0.8%; total: 10 ± 0.8%	NR	NR
NR	NR	11: 0.3 ± 9.3%; 12: 1.4 ± 10.1%; 21: 0.6 ± 9.3%; 22: 1.8 ± 10.9%; total: 1.02 ± 9.9%	NR	NR
NR	NR	11,21: 6.80 ± 3.90%; 12,22: 7.08 ± 3.86%; total: 6.94 ± 3.88%	NR	NR
Radiographs were taken before and after treatment with the same radiographic machine (Siemens, Sidexis XG, Germany)	Malmgren	11: 0.36 ± 0.19 mm; 12: 0.28 ± 0.03 mm; 21: 0.36 ± 0.25 mm; 22: 0.29 ± 0.09 mm; total: 0.32 ± 0.14	0: 9.18%; 1: 32.65%; 2: 38.77%; 3: 11.22%; 4: 8.16%	90.82%
64–66 kVp; 6–9 mA; 10 s	Gay et al.; rRCR ≥ 100% presenting no EARR; rRCR = 90–99% slight EARR; rRCR = 80–90% moderate EARR; rRCR < 80% severe EARR	NR	11,12,21,22: Severe: (n: 13) 11%; moderate: (n: 22) 18%; slight: (n: 26) 22%; no EARR: (n: 59) 49%	11: 53.33%; 12: 46.6%; 21: 46.6%; 22: 56.6%
NR	EARR: 0.90 > rRCR < 1; no EARR: rRCR > 0.90	Total: rRCR < 0.80: 2.97% (12); 0.80 < rRCR < 0.90: 5.91% (34); 0.90 < rRCR < 1: 86.88% (351); rRCR < 1: 1.73% (7)	Total: rRCR < 0.80: 2.97% (12); 0.80 < rRCR < 0.90: 5.91% (34); 0.90 < rRCR < 1: 86.88% (351); rRCR < 1: 1.73% (7)	Total: rRCR < 0.80: 2.97% (12); 0.80 < rRCR < 0.90: 5.91% (34); 0.90 < rRCR < 1: 86.88% (351); rRCR < 1: 1.73% (7)
NR	EARR > 2 mm; no EARR < 2 mm	2.9 ± 2.4 mm	EARR > 2 mm: (n: 59) 50%; EARR < 2 mm: (n: 59) 50%	EARR > 2 mm: (n: 59) 50%; EARR < 2 mm: (n: 59) 50%
NR	EARR was recorded when at least 20% of the root length of at least 1 incisor had been lost with orthodontic treatment.	EARR: 27% (n: 53)	NR	27%
NR	Malmgren	Degree of root resorpion difference in Malmgren: 12: 1.73 ± 0.79; 11: 1.59 ± 0.74; 21: 1.59 ± 0.74; 22: 1.72 ± 0.80; total: 1.65 ± 0.76	NR	NR

Table 2. Characteristics of Included Studies That Used Panoramic Radiography for the Diagnosis of External Apical Root Resorption (EARR)

Author (Year)	Location	Sample Size, Upper Incisors Roots Measured	Sample Size, Patients	Treatment Duration, mo
Sharpe et al. (1987)[13]	NY, USA	72	36	37.4
McFadden et al. (1989)[30]	Göteborg, Sweden	38	38	28.8 ± 7.4
Remington et al. (1989)[32]	Wash, USA	11,21: 198; 12,22: 191; total: 389	100	26.4 ± 9.5
Linge and Linge (1991)[3]	Skien, Norway	12: 428 teeth; 11: 422 teeth; 21: 392 teeth; 22: 414 teeth; total: 1656	485	12: 10.5 ± 7; 11: 12.2 ± 7.6; 21: 12.2 ± 7.5; 22: 10.8 ± 7; total: 11.42 ± 7.2
Mirabella and Artun (1995)[9]	Wash, USA	11,21: 299; 12,22: 290; total: 589	343	24 ± 8.3
Blake et al. (1995)[23]	Toronto, Canada	252	63	20.8 ± 4.5
Lupi et al. (1996)[27]	Chicago, Ill, USA	11,21: 166; 12,22: 161; total: 327	88	20
Taithongchai et al. (1996)[35]	Bangkok and Nonthaburi, Thailand, and St. Louis, Mo, USA	800	400	20.96 ± 8.35
Reukers et al. (1998)[33]	Nijmegen, Netherlands.	61	61	20.4 ± 5.3
Sameshima and Sinclair (2001)[34]	Los Angeles, Calif, USA	867	868	31.4 ± 7.4
van Loenen et al. (2007)[37]	Ghent, Belgium	11,21: 50; 12,22: 49; total: 99	31	27.6 ± 6
Bellamy et al. (2008)[22]	Seattle, Wash, USA	87	43	28
Artun et al. (2009)[21]	Safat, Kuwait.	997	267	24.9 ± 7.3
Liou and Chang (2010)[26]	Taipei, Taiwan	80	20	22.7 ± 5.0
Picanço et al. (2011)[31]	Brazil	99	99	43.14 ± 11.1
Martins et al. (2012)[28]	São Paulo, Bauru, Brazil	224	56	28.69 ± 8.25
Zahedani et al. (2013)[38]	Shiraz, Irán.	375	127	23.98
Zawawi and Malki (2014)[39]	Jedda, Saudi Arabia	80	40	21.5 ± 3.39
Maues et al. (2015)[29]	Rio de Janeiro, Brazil	11: 121; 12: 118; 21: 120; 22: 118; total: 477	129	85.79 ± 47.63
Chen et al. (2015)[24]	Zhejiang, China	280	70	20.43 ± 3.51
Tehranchi et al. (2017)[36]	Fort Lauderdale, Fla, USA	11: 34; 12: 34; 21: 34; 22: 34; total: 136	34	46.91 ± 20.03
Kim et al. (2018)[25]	Seoul, South Korea	11,21: 135; 22,12: 135; total: 270	135	25.7 ± 10.5

[a] ARR indicates apical root resorption; CEJ, cementoenamel junction; CF, correction factor; NR, Not reported; RR, Root resorption; TL, Tooth Lenght.

Table 2. Extended

EARR Measurement Method	EARR Measurement Program	Rx Parameters
Sharpe's method (scale)	Visual; Sharpe	NR
Linge and Linge[3] (mm and %)	Measurements were done with good illumination and electronic measuring calipers (resolution to 0.01 mm and accuracy to 0.03 mm).	NR
Malmgren et al.[12] (scale)	NR	NR
Linge and Linge[3] (mm)	Directly from the radiographs	NR
Mirabella (mm)	Radiographs were projected onto a screen at approximately 7 × magnification. Linear measurements were made with a transparent ruler to the nearest 0.14 mm, the nearest whole millimeter on the magnified image.	NR
Linge and Linge[3] (%)	A specialized measuring instrument called the Comparitor (Edmund Scientific Co., Barrington, NJ, USA) was used. It has a 6 × eyepiece with a 20 mm scale etched onto the viewing surface.	NR
Sharpe et al.[13] (scale)	Visual; Sharpe	NR
Linge and Linge[3] (mm)	Each pretreatment and posttreatment periapical radiograph of the maxillary central incisors was enlarged 10 × by projection and traced.	NR
Own method: To correct for different projection angles that are a consequence of the bisecting-angle technique, the radiographs were digitally processed. After reconstruction of the digital images, the (relative) tooth lengths could be measured as the number of pixels on the screen. The percentage loss of tooth length was calculated as (L1 − L2)/LI (L1 = tooth length before treatment; L2 = tooth length at the end of fixed appliance therapy), (%).	NR	NR
Mirabella (mm)	Full-mouth periapical films were scanned then viewed at double magnification on a large color monitor with 0.25 dot pitch fineness. Root length was measured on the scanned images from the apex to the midpoint of the right and left CEJs with Sigma Scan (SPSS Scientific, Chicago, Ill, USA).	NR
CF: The edge of the bracket, CEJ, and root apices were marked and used to define crown and root length. The ARR ratio was calculated as follows (Figure 1): C1/C2 ×·R2/R1, where C is the crown length and R the root length at different time points. When a tooth showed no root resorption during the different treatment periods, the ARR ratio was classified as 1 (mm).	Jasc® Paint Shop Pro 7TM (Eden Prairie, Minn, USA)	Radiographs were developed, magnified (3×), and digitized using Agfa ScanWise 1.2.0.5® (Mortsel, Belgium).
Apex-CEJ (following the long axis), (mm)	ImageJ	NR
Own method: The protocol called for 3 radiographic projections, 1 with the central ray between the 2 central incisors, and 1 with the ray centered at the lateral incisor on either side, made according to a paralleling technique. Then correction reconstruction and superimposition of the images. TL was measured as the distance from the apex tip to the midpoint of either the incisal edge or the line connecting the mesial and distal outlines of CEJ, depending on the location of the incisal reference points used for reconstruction (mm)	Emago software, recording the number of pixels between landmark pairs	NR
Linge and Linge[3] (mm and %)	ImageJ	NR
Apex-CEJ (following the long axis), (mm and %)	Dolphin Imaging Premium 10.5 (Dolphin Imaging & Management Solutions, Chatsworth, Calif, USA)	NR
Malmgren et al.[12] (scale)	Scanned with the Sprint Scan 35 Plus scanner (version 2.7.2; Polaroid, Cambridge, Mass, USA), with a resolution of 675 dpi at a scale of 1:1. Images were analyzed with Photoshop software (version 6.0; Adobe System, San Jose, Calif, USA) at 300% enlargement, without image quality loss.	NR
Apex-CEJ (following the long axis), (%)	Photoshop S3	NR
Linge and Linge[3] (mm)	Sirona Sidexis software	NR
Malmgren et al.[12] (scale)	Visual; Malmgren; x-ray viewer with standard light intensity, equipped with a 5 × magnification loop (Cristófoli Equipamentos de Biossegurança Ltda., Campo Mourão, Paraná, Brazil)	NR
Linge and Linge[3] (mm and %)	Measures were performed to the nearest 0.01 mm, using the image analysis system (Siemens, Sidexis XG, Germany)	NR
Linge and Linge[3] modified by Brezniak et al.[10] (%)	Digital radiographs were visualized and analyzed through Photoshop CS (Adobe Systems Inc., San Jose, Calif, USA). To measure the distances, a proprietary tool was developed on MATLAB's image processing toolbox (MATLAB 7.14 2012a, Mathworks Inc., Natick, Mass, USA).	Digital x-ray unit (MinRay, Soredex, Helsinki, Finland (10 kvp at 8 mA, 0.1 S); processor: Acteon PSPIX, France) at the same distance and using the same exposure settings (70–85 kVp at 10 Ma)
Own method: Apex-CEJ with CF: Pretreatment tooth length (R1) was measured along the long axis connecting the midpoint of the incisal edge (M) and the root apex, and the intersection angle (h) between the incisal edge and the long axis was recorded. Posttreatment tooth length (R2) was measured along the long axis originating from M with an intersection angle of h to the incisal edge. The CF was calculated as the ratio of the pretreatment ball height (B1) and the posttreatment ball height (B2) to correct any differences in image magnification or distortion between pretreatment and posttreatment radiographs. ARR was calculated as follows: CF = B1/B2. ARR = R1 − (R2 × CF), (mm)	Image J 1.43u software program (Wayne Rasband, National Institutes of Health, Bethesda, Md) with B1 height defined as 4 mm	NR

Table 2. Extended

EARR Definition and Severity	Mean EARR Founded	Severity of EARR, %	Prevalence of EARR
Severity according to Sharpe's method (scale)	Sharpe's method media score: 0.72 ± 0.165	NR	41.65%
NR	1.84 mm/13.2%	NR	NR
Malmgren	Total: (n: 389); 0: 15 (4%); 1: 19 (5%); 2: 255 (65%); 3: 90 (23%); 4: 10 (3%)	Total: (n: 389); 0: 15 (4%); 1: 19 (5%); 2: 255 (65%); 3: 90 (23%); 4: 10 (3%)	11,21 (n: 198): 0: 1%; 1,2,3,4: 99%; 12,22 (n: 191): 0: 6%; 1,2,3,4: 94%
RR > 0 mm	12: 1 ± 1 mm; 11: 0.8 ± 0.9 mm; 21: 0.7 ± 0.9 mm; 22: 1 ± 1 mm; total: 0.87 ± 1 mm	80 patients (16.5%) had root shortenings > 2.5 mm for 1 or more maxillary incisors.	n: 1656 teeth; 89% RR > 0 mm
Severity from −1 to 9 mm RR	11,21 (n: 299): 1.12 ± 1.39 mm; 12,22 (n: 290): 1.23 ± 1.25 mm; total: 1.22 ± 1.32 mm	NR	NR
Root resorption was defined as any reduction in the radiographic length of the maxillary and mandibular incisor teeth from the tip of the incisal edge to the apex of the root.	12,22: 12.52% ± 8.88; 11,21: 8.35% ± 7.68; total: 10.47% ± 8.28	NR	NR
Sharpe's method	Total (n: 327); pretreatment/posttreatment: 0: 259/78 (79%/23%); 1: 60/158 (18%/48%); 2: 7/79 (2%/24%); 3: 1/12 (0.5%/3.5%)	Total (n: 327); pretreatment/posttreatment: 0: 259/78 (79%/23%); 1: 60/158 (18%/48%); 2: 7/79 (2%/24%); 3: 1/12 (0.5%/3.5%)	Total (n: 327); pretreatment/posttreatment: 0: 259/78 (79%/23%); 1: 60/158 (18%/48%); 2: 7/79 (2%/24%); 3: 1/12 (0.5%/3.5%)
NR	21: 1.96 ± 1.33 mm; 11: 2.11 ± 1.37 mm; total: 2.04 ± 1.22 mm	2% of the patients in the present sample lost > 5 mm.	NR
NR	7.8% ± 6.9	NR	65.00%
NR	11,21: 1.17 ± 1.14 mm; 12,22: 1.43 ± 1.27 mm	NR	NR
NR	11,21: 0.89 ± 0.08 mm; 12,22: 0.85 ± 0.10 mm; total: 0.87 ± 0.09 mm	NR	11,21: 70%; 12,22: 76%
NR	Total: 0.43 ± 0.14 mm	NR	NR
NR	12: 1.24 ± 1.26 mm; 11: 1.01 ± 1.05 mm; 21: 0.88 ± 1.17 mm; 22: 0.95 ± 1.17 mm; total: 1.10 ± 1.02 mm	>5 mm	<2 mm: 76.8%; >2 mm: 16.5%; >3 mm: 5.2%; >4 mm: 1.5%
Shortening of the original root length. ARR (mm) = C1/C2 (R1 − R2); ARR (%) = C1/C2 (R1 − R2)/R1	12: 2.1 ± 1.4 mm (14.4 ± 7.3%); 11: 2.1 ± 1.5 mm (13.6 ± 7.6%); 21: 2.1 ± 1.3 mm (13.4 ± 7.3%); 22: 2.3 ± 1.7 mm (13.6 ± 7.6%); total: 2.15 ± 1.4 mm	NR	NR
Malmgren	2.06 ± 0.94 mm (0.17% ± 0.09)	The sample is divided by severity.	The sample is divided by severity.
Malmgren	Malmgren: 0: 0% (n: 0); 1: 28% (n: 62); 2: 43% (n: 97); 3: 26% (n: 58); 4: 3% (n: 7)	Malmgren: 0: 0% (n: 0); 1: 28% (n: 62); 2: 43% (n: 97); 3: 26% (n: 58); 4: 3% (n: 7)	100.00%
NR	11,21: 16.76%; 12,22: 16.99%	NR	NR
Malmgren	11,21: 0.99 ± 0.11 mm	No RR: 32.5%; mild (<2 mm): 56.2%; moderate (>2 and > 1/3 of root): 8.8%; severe (>1/3 of root): 2.5%	67.5%
Malmgren	Total: (n: 457); 0: 98 (20%); 1: 73 (15%); 2: 191 (44%); 3: 69 (14%); 4: 26 (7%)	Total: (n: 457); 0: 98 (20%); 1: 73 (15%); 2: 191 (44%); 3: 69 (14%); 4: 26 (7%)	Total: (n: 457); 0: 98 (20%); 1: 73 (15%); 2: 191 (44%); 3: 69 (14%); 4: 26 (7%)
Malmgren	11,21: 0.4 ± 0.3 mm (3.37%); 12,22: 0.25 ± 0.4 mm (2.30%); total: 0.32 ± 0.35 mm (2.83%)	NR	100.00%
NR	21: 0.91 ± 0.08 mm/8.49 ± 8.77%; 11: 0.88 ± 0.09 mm/11.88 ± 9.37%; 22: 0.85 ± 0.11 mm/14.04 ± 11.40%; 12: 0.87 ± 0.10 mm/12.45 ± 10.10%; total: 0.87 ± 0.10/11.71 ± 9.91%	NR	NR
NR	11,21: 1.09 ± 0.49 mm; 12,22: 1.08 ± 0.52 mm; total: 1.08 ± 0.50 mm	NR	NR

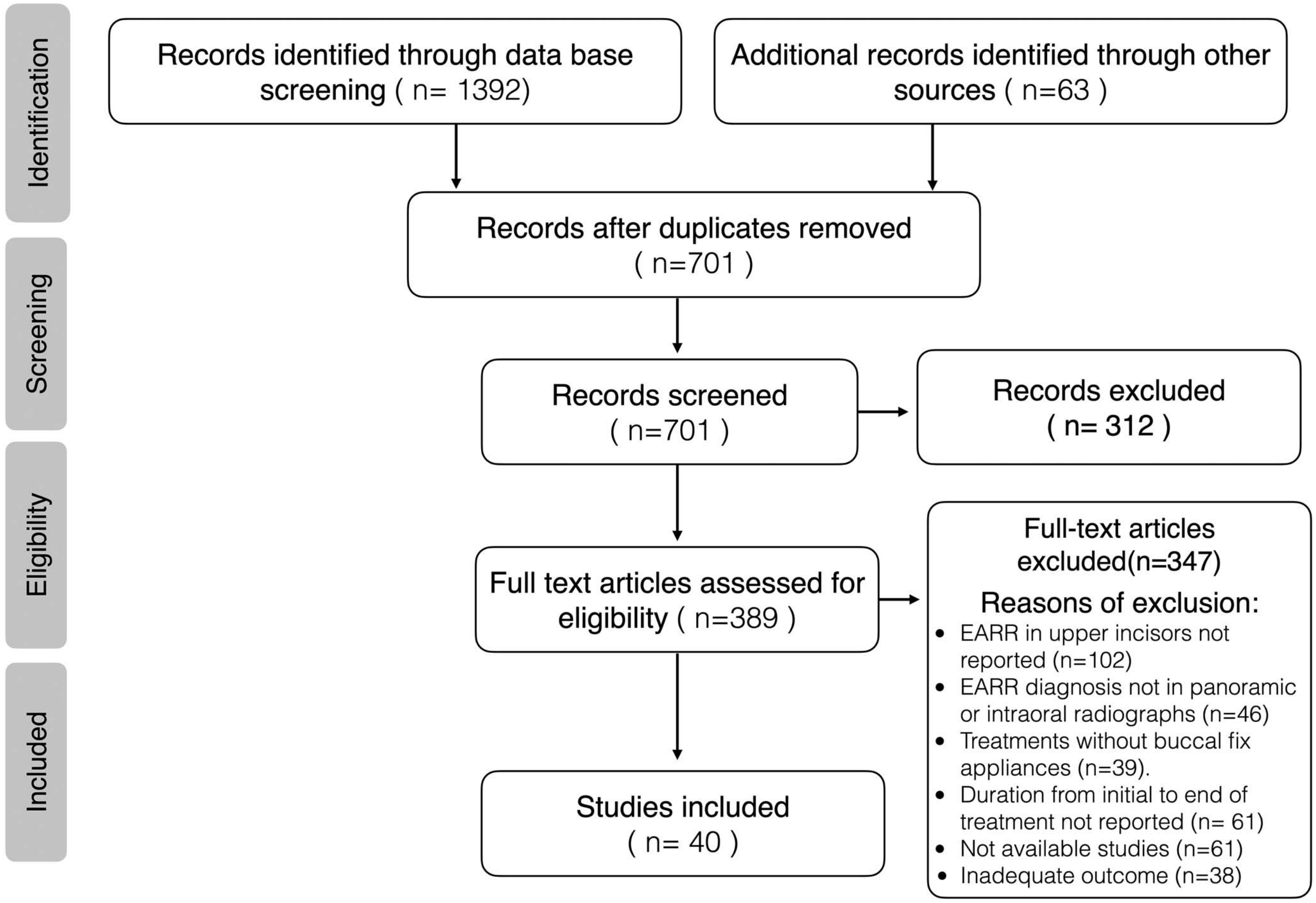


Figure 1. Flow diagram for the scoping review process adapted from the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement by Moher et al. (2009).[57]

RESULTS

Search Results

The search strategy yielded 704 studies, of which 3 were duplicates. Following the PCC criteria, screening by title and abstract yielded 389 articles for full-text review, and 40 studies were finally included in this review.[3,4,8,9,11,13,21–54] The PRISMA flowchart in Figure 1 illustrates the process. Reasons for exclusion are summarized and described in Appendix 2.

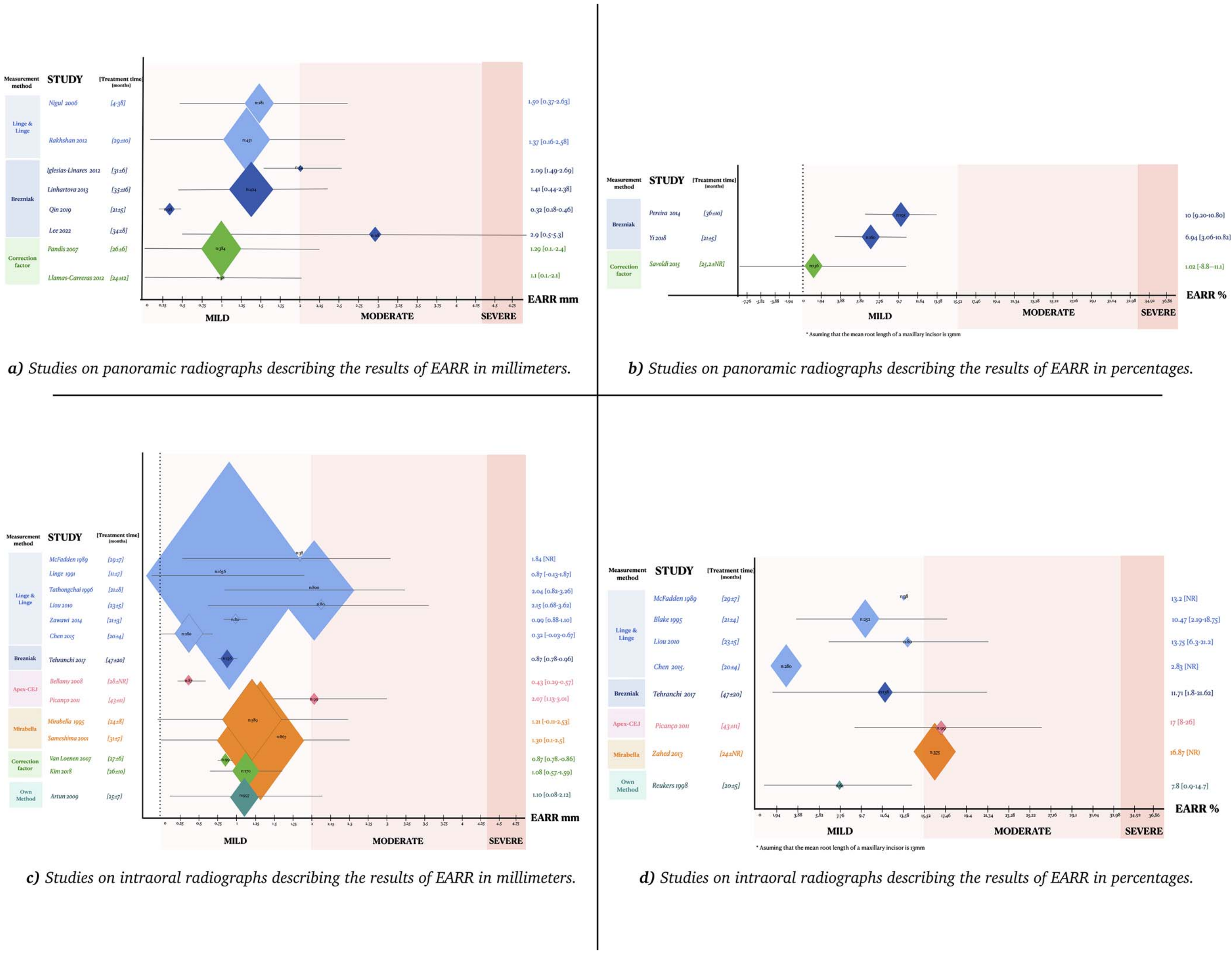
Characteristics of Included Studies (Type of Radiographic Method and Sample Size)

After screening and checking that the studies met the inclusion criteria, 40 studies were finally selected. All the included publications were categorized according to type of radiograph used to diagnose EARR: authors of 18 studies used panoramic radiographs,[4,8,11,40–54] and authors of 22 studies used intraoral radiographs.[3,9,13,21–39] The studies included according to radiographic method, panoramic radiographs or intraoral radiographs, are synthesized and summarized in Tables 1 and 2, respectively.

For sample size, an important distinction was made between the number of patients analyzed in the studies and the number of roots measured to determine EARR. The mean number of patients treated in the studies was 130. For the number of roots measured, Pamukçu et al.[49] examined only 30 roots, whereas Linge and Linge[3] studied 1656.

EARR (Definition and Threshold Values, Type of Results, and Severity)

A bewildering array of techniques and perspectives exists for diagnosing and estimating EARR. While some researchers set the threshold for defining EARR at 2 mm[42] of apical root loss, others[52] considered even minimal losses of 1.20 mm as significant. Surprisingly, some even suggested the onset of EARR as early as 0.1 mm.[41,49] The adoption by some investigators of severity scales of Malmgrem et al.[12] or Sharpe et al.[13] introduced further complexity into the assessment of EARR.



a) Studies on panoramic radiographs describing the results of EARR in millimeters.

b) Studies on panoramic radiographs describing the results of EARR in percentages.

c) Studies on intraoral radiographs describing the results of EARR in millimeters.

d) Studies on intraoral radiographs describing the results of EARR in percentages.

Figure 2. Studies on panoramic and intraoral radiography describing the results of external apical root resorption (EARR) in millimeters or percentages.

The EARR results compiled in Figure 2 provide interesting data and insights into the diagnosis of EARR. The findings are mostly presented in millimeters or percentages and vary from study to study. More particularly, Chen et al.[24] and Qin et al.[4] reported minimal mean EARR values (0.32 ± 0.14 mm), which contrasted with Lee et al.,[11] who reported notably higher measurements (2.9 ± 2.4 mm). In terms of percentage measurements, Picanço et al.[31] reported the lowest EARR (0.17% ± 0.09), whereas Zahedani et al.[38] reported the highest (16.87%).

Measurement Method, Software Analysis, and Radiographic Parameters

The most commonly used method for measuring EARR was that developed by Linge and Linge[3] modified by Brezniak et al.,[10] employed in 25%, followed by the original Linge and Linge[3] method, used in 22.5% of the studies. The prevalence of usage of each measurement method is presented in Appendix 3.

The software or direct measurement methods used for assessments were varied and numerous, and additionally, other authors developed their own software for measurement. (Tables 1 and 2).

Authors of only two studies[36,49] reported the exact radiographic parameters used for x-ray imaging; however, these parameters varied considerably depending on the type of radiograph taken.

Duration of Treatment as a Cofounding Factor Associated with EARR

The mean duration of orthodontic treatment across the 40 studies was 28.10 months. Treatment duration was found to be positively correlated with the amount of EARR in 13 studies and not associated in five. Authors of the remaining studies did not analyze treatment duration as a factor related to the amount of EARR. However, no relationship was found between the measurement method and the studies in which authors affirmed a correlation of treatment time with EARR.

DISCUSSION

After reviewing the results of this study, it was clear from the literature that no common criteria existed for the diagnosis of EARR. Some authors[25] used periapical radiographs for diagnosis, whereas others[54] used panoramic radiography. Different methods for EARR measurement were reported, some using the incisal edge as a correction factor (CF)[25] and others[54] using the modified Linge and Linge[3] method by Brezniak et al.[10] The assessment method also varied, with some expressing results in millimeters and others reporting EARR in percentages. With all of the differences in diagnostic techniques, measurement methods, and units, it could be concluded that the discrepancies in the scientific literature came from many different sources.

It should be noted that the study designs of the included studies did not differ, but notable differences existed in sample size among the studies and a wide range of teeth examined in each study; this could compromise the representativeness of the results. To mitigate these differences and strive for consistency, in this study, we only included studies that focused on maxillary incisors, which are not only the teeth most commonly used in studies focusing on EARR but are also more prone to EARR.[14] Additionally, treatment duration has been extensively discussed in the literature as a factor influencing EARR, and considerable variability existed in the findings. Due to this, in the current review, only studies that reported full treatment duration from initiation to completion were included to ensure consistency and avoid biases from partial treatment evaluations.[6,16,17]

The use of CBCT is currently not a feasible alternative to routine panoramic views, mainly for economic and ethical reasons, particularly in young patients.[8,58] Consequently, panoramic and periapical radiographs are still the preferred imaging modalities for diagnostic purposes and for routine assessment of root resorption.[8] Nevertheless, some concerns have been raised regarding the potential overestimation of root loss by panoramic radiographs compared with intraoral radiographs, with authors of some studies suggesting an overestimation of 20% or more.[34] In the present study, panoramic radiographs showed an average EARR of 1.49 mm compared with 1.22 mm in periapical radiographs. It should be noted, however, that this difference could be attributed to possible overestimation by panoramic radiographs or to inherent variability in the results of the studies themselves. This could be attributed, in part, to proclination of the upper incisors, which was not verified by measuring proclination on cephalometric radiographs. Hence, it would be of great interest to include incisor proclination as a factor in the formula for calculating resorption when using panoramic radiographs to diagnose EARR.[59]

The use of different measurement methods in different studies is a significant source of bias when interpreting the results. Katona (2007)[60] demonstrated that compensatory algorithms for EARR assessment, including assumed parallel x-ray beams, resulted in inaccuracies when the source was at a finite distance. As these methods remain widely used, their limitations must also be acknowledged when analyzing contributing factors. However, it should be noted that the cementoenamel junction (CEJ) can be used as a reliable landmark for correction, and some authors[34] concluded that its identification is often challenging in radiographs. Despite this, authors of a surprising 62% of the studies analyzed in this review used it to diagnose EARR. Some authors[25] used a metal ball cemented to the tooth, whereas others[41] used the mesiodistal size of the molar.

The lack of consistency in the current literature highlights the urgent need for consensus on EARR diagnostic methods, measurement techniques, and interpretation criteria. Variability across studies leads to discrepancies in prevalence rates and treatment outcomes, hindering the creation of standardized clinical protocols. Collaborative efforts among researchers, clinicians, and professional organizations are essential to develop universally accepted guidelines for imaging modalities, measurement standardization, and clear criteria for EARR severity. Establishing these standardized protocols will enhance research comparability, improve diagnostic accuracy, and facilitate better monitoring and management. Given the discrepancies in imaging modalities and measurement techniques, prioritizing periapical radiographs and incorporating cephalometric analysis to account for incisor proclination could improve diagnostic reliability. A unified approach will strengthen clinical decision-making and lead to more effective prevention and management strategies in orthodontic practice.

The findings revealed a notable lack of consensus among the authors of the studies reviewed regarding the diagnosis and methods of measurement of root resorption (EARR). In addition, the variability of the measurement techniques suggests that no single method consistently provides comparable results. This inconsistency poses a major challenge to the accurate assessment and management of root resorption in clinical practice. Resolving this issue is critical to improving diagnostic accuracy, treatment planning, and ultimately, patient outcomes in orthodontic care. Future researchers should focus on standardizing diagnostic protocols and refining measurement techniques to establish a more uniform approach for assessing root resorption using two-dimensional (2D) radiography.

CONCLUSIONS

- In the orthodontic literature, a wide range of assessment methods for EARR has been described, from traditional 2D and 3D radiographic techniques to innovative approaches such as biomarker-based detection or aided by artificial intelligence.
- Considerable variability exists in the methods used to measure EARR across studies, with some using CFs and others relying on perceptual assessment to classify severity.
- Patient- and treatment-related factors such as treatment duration are inconsistently associated with the development of EARR.
- Standardization of diagnostic criteria, measurement methods, and severity classification is essential to increase reliability and comparability between studies and to improve clinical management of EARR.

SUPPLEMENTAL DATA

Appendices 1 through 3 are available online.

DISCLOSURES

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This study was conducted under a pre-doctoral teaching and research contract (0103/AYU/003) at Complutense University of Madrid.

ACKNOWLEDGMENT

The authors thank Prof Carlos Flores-Mir for his guidance and significant contributions to the completion of this review.

REFERENCES

1. Alam F, Chauhan AK, Sharma A, Verma S, Raj Y. Comparative cone-beam computed tomographic evaluation of maxillary incisor intrusion and associated root resorption: intrusion arch vs mini-implants. *Am J Orthod Dentofacial Orthop.* 2023;163(3):e84–e92.
2. Almagrami I, Almashraqi AA, Almaqrami BS, et al. A quantitative three-dimensional comparative study of alveolar bone changes and apical root resorption between clear aligners and fixed orthodontic appliances. *Prog Orthod.* 2023;24(1):6.
3. Linge L, Linge BO. Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. *Am J Orthod Dentofacial Orthop.* 1991;99(1):35–43.
4. Qin F, Zhou Y. The influence of bracket type on the external apical root resorption in class I extraction patients—a retrospective study. *BMC Oral Health.* 2019;19(1):53.
5. Tan JHS, Yazid F, Kasim NA, Ariffin SHZ, Wahab RMA. A newly developed kit for dental apical root resorption detection: efficacy and acceptability. *BMC Oral Health.* 2024;24(1):298.
6. 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(1):67–79.
7. Pereira SA, Corte-Real A, Melo A, Magalhaes L, Lavado N, Santos JM. Diagnostic accuracy of cone beam computed tomography and periapical radiography for detecting apical root resorption in retention phase of orthodontic patients: a cross-sectional study. *J Clin Med.* 2024;13(5):1248.
8. Kaya B, Gulsahi A, Turkyilmaz G. Factors that may increase the risk of external apical root resorption during orthodontic treatment: retrospective clinical investigation. *J Orofac Orthop.* 2023;85:425–434.
9. Mirabella AD, Artun J. Risk factors for apical root resorption of maxillary anterior teeth in adult orthodontic patients. *Am J Orthod Dentofacial Orthop.* 1995;108(1):48–55.
10. Brezniak N, Goren S, Zoizner R, et al. The use of an individual jig in measuring tooth length changes. *Angle Orthod.* 2004;74(6):780–785.
11. Lee YJ, Pak H, Hwang CJ, et al. Targeted next-generation sequencing for comprehensive genetic analysis of external apical root resorption during orthodontic treatment with premolar extraction in the Korean population. *Am J Orthod Dentofacial Orthop.* 2022;162(5):668–679.e5.
12. Malmgren O, Goldson L, Hill C, Orwin A, Petrini L, Lundberg M. Root resorption after orthodontic treatment of traumatized teeth. *Am J Orthod.* 1982;82(6):487–491.
13. Sharpe W, Reed B, Subtelny JD, Polson A. Orthodontic relapse, apical root resorption, and crestal alveolar bone levels. *Am J Orthod Dentofacial Orthop.* 1987;91(3):252–258.
14. Sameshima GT, Iglesias-Linares A. Orthodontic root resorption. *J World Fed Orthod.* 2021;10(4):135–143.
15. Iber-Diaz P, Senen-Carramolino R, Iglesias-Linares A, Fernandez-Navarro P, Flores-Mir C, Yanez-Vico RM. GWAS of post-orthodontic aggressive external apical root resorption identified multiple putative loci at X-Y chromosomes. *J Pers Med.* 2020;10(4):169.
16. Segal GR, Schiffman PH, Tuncay OC. Meta analysis of the treatment-related factors of external apical root resorption. *Orthod Craniofac Res.* 2004;7(2):71–78.
17. Linkous ER, Trojan TM, Harris EF. External apical root resorption and vectors of orthodontic tooth movement. *Am J Orthod Dentofacial Orthop.* 2020;158(5):700–709.
18. Peters MDJ, Marnie C, Tricco AC, et al. Updated methodological guidance for the conduct of scoping reviews. *JBI Evid Synth.* 2020;18(10):2119–2126.
19. Tricco AC, Lillie E, Zarin W, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): checklist and explanation. *Ann Intern Med.* 2018;169(7):467–473.
20. Doré J, Multon MC, Béhier JM; les participants à la table ronde 1 des Ateliers de Giens XXXII. Microbiote intestinal: qu'en attendre au plan physiologique et thérapeutique? *Therapie.* 2017;72(1):1–19.
21. Artun J, Van 't Hullenaar R, Doppel D, Kuijpers-Jagtman AM. Identification of orthodontic patients at risk of severe apical root resorption. *Am J Orthod Dentofacial Orthop.* 2009;135(4):448–455.

22. Bellamy LJ, Kokich VG, Weissman JA. Using orthodontic intrusion of abraded incisors to facilitate restoration: the technique's effects on alveolar bone level and root length. *J Am Dent Assoc.* 2008;139(6):725–733.
23. Blake M, Woodside DG, Pharoah MJ. A radiographic comparison of apical root resorption after orthodontic treatment with the edgewise and Speed appliances. *Am J Orthod Dentofacial Orthop.* 1995;108(1):76–84.
24. Chen W, Haq AA, Zhou Y. Root resorption of self-ligating and conventional preadjusted brackets in severe anterior crowding Class I patients: a longitudinal retrospective study. *BMC Oral Health.* 2015;15:115.
25. Kim KW, Kim SJ, Lee JY, et al. Apical root displacement is a critical risk factor for apical root resorption after orthodontic treatment. *Angle Orthod.* 2018;88(6):740–747.
26. Liou EJ, Chang PM. Apical root resorption in orthodontic patients with en-masse maxillary anterior retraction and intrusion with miniscrews. *Am J Orthod Dentofacial Orthop.* 2010;137(2):207–212.
27. Lupi JE, Handelman CS, Sadowsky C. Prevalence and severity of apical root resorption and alveolar bone loss in orthodontically treated adults. *Am J Orthod Dentofacial Orthop.* 1996;109(1):28–37.
28. Martins DR, Tibola D, Janson G, Maria FR. Effects of intrusion combined with anterior retraction on apical root resorption. *Eur J Orthod.* 2012;34(2):170–175.
29. Maues CP, do Nascimento RR, Vilella Ode V. Severe root resorption resulting from orthodontic treatment: prevalence and risk factors. *Dental Press J Orthod.* 2015;20(1):52–58.
30. McFadden WM, Engstrom C, Engstrom H, Anholm JM. A study of the relationship between incisor intrusion and root shortening. *Am J Orthod Dentofacial Orthop.* 1989;96(5):390–396.
31. Picanço GV, de Freitas KM, Cançado RH, Valarelli FP, Picanço PR, Feijão CP. Predisposing factors to severe external root resorption associated to orthodontic treatment. *Dental Press J Orthod.* 2013;18(1):110–120.
32. Remington DN, Joondeph DR, Artun J, Riedel RA, Chapko MK. Long-term evaluation of root resorption occurring during orthodontic treatment. *Am J Orthod Dentofacial Orthop.* 1989;96(1):43–46.
33. Reukers EA, Sanderink GC, Kuijpers-Jagtman AM, van't Hof MA. Radiographic evaluation of apical root resorption with 2 different types of edgewise appliances. Results of a randomized clinical trial. *J Orofac Orthop.* 1998;59(2):100–109.
34. Sameshima GT, Sinclair PM. Predicting and preventing root resorption: part II. Treatment factors. *Am J Orthod Dentofacial Orthop.* 2001;119(5):511–515.
35. Taithongchai R, Sookkorn K, Killiany DM. Facial and dentoalveolar structure and the prediction of apical root shortening. *Am J Orthod Dentofacial Orthop.* 1996;110(3):296–302.
36. Tehranchi A, Sadighnia A, Younessian F, Abdi AH, Shirvani A. Correlation of vitamin D status and orthodontic-induced external apical root resorption. *Dent Res J (Isfahan).* 2017;14(6):403–411.
37. van Loenen M, Dermaut LR, Degrieck J, De Pauw GA. Apical root resorption of upper incisors during the torquing stage of the tip-edge technique. *Eur J Orthod.* 2007;29(6):583–588.
38. Zahedani SMZ, Oshagh M, Danaei ShM, Roeinpeikar SMM. A comparison of pical root resorption in incisors after fixed orthodontic treatment with standard edgewise and straight wire (MBT) method. *J Dent (Shiraz).* 2013;14(3):103–110.
39. Zawawi KH, Malki GA. Radiographic comparison of apical root resorption after orthodontic treatment between bidimensional and Roth straight-wire techniques. *J Orthod Sci.* 2014;3(4):106–110.
40. Alexander SA. Levels of root resorption associated with continuous arch and sectional arch mechanics. *Am J Orthod Dentofacial Orthop.* 1996;110(3):321–324.
41. Baghaei NN, Zhai G, Lamani E. Genetic and other factors contributing to external apical root resorption in orthodontic patients. *Orthod Craniofac Res.* 2023;26(Suppl 1):64–72.
42. Ciurla A, Szymanska J, Plachno BJ, Bogucka-Kocka A. Polymorphisms of encoding genes *IL1RN* and *P2RX7* in apical root resorption in patients after orthodontic treatment. *Int J Mol Sci.* 2021;22(2):777.
43. Iglesias-Linares A, Yanez-Vico R, Ballesta-Mudarra S, et al. Postorthodontic external root resorption is associated with IL1 receptor antagonist gene variations. *Oral Dis.* 2012;18(2):198–205.
44. Iglesias-Linares A, Yanez-Vico RM, Moreno-Fernandez AM, Mendoza-Mendoza A, Orce-Romero A, Solano-Reina E. Osteopontin gene SNPs (rs9138, rs11730582) mediate susceptibility to external root resorption in orthodontic patients. *Oral Dis.* 2014;20(3):307–312.
45. Jacobs C, Gebhardt PF, Jacobs V, Hechtner M, Meila D, Wehrbein H. Root resorption, treatment time and extraction rate during orthodontic treatment with self-ligating and conventional brackets. *Head Face Med.* 2014;10:2.
46. Linhartova P, Cernochova P, Izakovicova Holla L. IL1 gene polymorphisms in relation to external apical root resorption concurrent with orthodontia. *Oral Dis.* 2013;19(3):262–270.
47. Llamas-Carreras JM, Amarilla A, Espinar-Escalona E, et al. External apical root resorption in maxillary root-filled incisors after orthodontic treatment: a split-mouth design study. *Med Oral Patol Oral Cir Bucal.* 2012;17(3):e523–e527.
48. Nigul K, Jagomagi T. Factors related to apical root resorption of maxillary incisors in orthodontic patients. *Stomatologija.* 2006;8(3):76–79.
49. Pamukcu H, Polat-Ozsoy O, Gulsahi A, Ozemre MO. External apical root resorption after nonextraction orthodontic treatment with labial vs. lingual fixed appliances. *J Orofac Orthop.* 2020;81(1):41–51.
50. Pandis N, Nasika M, Polychronopoulou A, Eliades T. External apical root resorption in patients treated with conventional and self-ligating brackets. *Am J Orthod Dentofacial Orthop.* 2008;134(5):646–651.
51. Pereira S, Lavado N, Nogueira L, Lopez M, Abreu J, Silva H. Polymorphisms of genes encoding P2X7R, IL-1B, OPG and RANK in orthodontic-induced apical root resorption. *Oral Dis.* 2014;20(7):659–667.
52. Rakhshan V, Nateghian N, Ordoubazari M. Risk factors associated with external apical root resorption of the maxillary incisors: a 15-year retrospective study. *Aust Orthod J.* 2012;28(1):51–56.
53. Savoldi F, Bonetti S, Dalessandri D, Mandelli G, Paganelli C. Incisal apical root resorption evaluation after low-friction orthodontic treatment using two-dimensional radiographic imaging and trigonometric correction. *J Clin Diagn Res.* 2015;9(11):ZC70–ZC74.

54. Yi J, Xiao J, Li Y, Li X, Zhao Z. External apical root resorption in non-extraction cases after clear aligner therapy or fixed orthodontic treatment. *J Dent Sci.* 2018; 13(1):48–53.
55. Fritz U, Diedrich P, Wiechmann D. Apical root resorption after lingual orthodontic therapy. *J Orofac Orthop*. Nov 2003; 64(6):434–442.
56. Gay G, Ravera S, Castroflorio T, et al. Root resorption during orthodontic treatment with Invisalign(R): a radiometric study. *Prog Orthod*. Dec 2017;18(1):12.
57. Moher D, Liberati A, Tetzlaff J, Altman DG; PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*. 2009:339:b2535. doi:10.1136/bmj.b2535
58. Benavides E, Krecioch JR, Connolly RT, et al. Optimizing radiation safety in dentistry: clinical recommendations and regulatory considerations. *J Am Dent Assoc.* 2024;155(4):280–293.e4.
59. Tieu LD, Normando D, Toogood R, Flores-Mir C. Impact on perceived root resorption based on the amount of incisal inclination as determined from conventional panoramic radiography. *Am J Orthod Dentofacial Orthop.* 2015;148(4):685–691.
60. Katona TR. The flaws in tooth root resorption assessment algorithms: the role of source position. *Dentomaxillofac Radiol.* 2007;36(6):311–316.