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Quantitative Measurement Approaches for External Apical Root Resorption Evaluation: A Review

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ABSTRACT

External Apical Root Resorption (EARR) is a common and unpredictable complication of orthodontic treatment. The occurrence of root resorption can aggravate the ratio between the crown and root, reduce tooth stability, and potentially lead to tooth loosening or loss. EARR caused by orthodontic treatment cannot be completely prevented, and its high incidence has garnered significant attention from orthodontists worldwide. Typically asymptomatic, root resorption is primarily detected through imaging, which can be regularly performed if necessary to identify and mitigate its progression early on. Apical radiography, panoramic radiography, and Cone Beam Computed Tomography (CBCT) are commonly utilized to assess the severity of EARR, with quantitative indicators such as root length, resorption area, and volume. This review summarizes the common indicators and methods for measuring EARR, aiming to provide a comprehensive perspective on its evaluation.

Keywords: External apical root resorption; Imaging; Diagnosis; Panoramic radiography; CBCT

INTRODUCTION

External Apical Root Resorption (EARR) is a complex inflammatory response resulting from multiple inducing factors, the direct cause of which is not fully understood, making it difficult to predict and impossible to completely prevent. Orthodontic-induced root resorption refers to EARR caused by various mechanical stimuli. Currently, radiographic examinations are the commonly used clinical evaluation methods. Different imaging techniques have their own advantages and disadvantages. Accurate and effective detection and measurement of EARR, along with timely adjustments to the treatment plan can help avoid severe EARR. This article mainly summarizes the commonly used evaluation methods of EARR in clinical practice, providing reliable suggestions for dentists to effectively assess the degree of root resorption [1].

MATERIALS AND METHODS

Root length

Changes in tooth length during orthodontic treatment directly reflect the amount of EARR. With the advancement of digital technology, the measurement of root length has evolved from traditional manual methods to direct measurement by computer software. Clinically, both two-dimensional imaging techniques, such as periapical films, panoramic radiography, and three-dimensional imaging techniques, such as Multi-Slice Spiral Computed Tomography (MSCT) and Cone Beam Computed Tomography (CBCT), can be used to measure the changes in root length. For measuring root length, the distance from the Cementoenamel Junction (CEJ) to the apex is typically measured directly as the root length. However, sometimes the position of the CEJ is difficult to determine. Therefore, some scholars use the difference between the highest point of the crown and the apex before and after treatment to indicate the amount of root resorption. Two-dimensional imaging can only detect changes in root length, but root morphology is often not visible due to image overlapping, which presents limitations for diagnosing root resorption in non-apical regions. In contrast, three-dimensional imaging can observe and measure roots from multiple directions, thus compensating for the shortcomings of two-dimensional imaging. For tooth length assessment, the sagittal slice selected was the one passing through the long axis of the tooth to be measured (Figure 1A). And if root curvature was observed, the measurements were calculated in a line

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following the curvature of the root (Figure 1B). The CBCT images were rotated when needed to determine the actual root length [2].

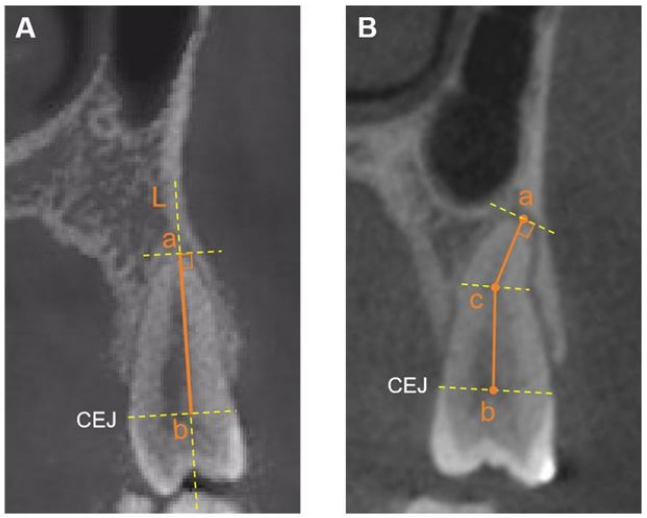


Figure 1: Root length is measured from the sagittal plane of CBCT. (A) The root length is the distance from point a to point b. a, root apex; b, the point of intersection of the long axis of the tooth (L line) and Cementoenamel Junction (CEJ); (B) When the root is curving, the root length is the sum of the distance from point a to point c and the distance from point c to point b. a, root apex; b, the midpoint of the CEJ; c, the midpoint of the line connecting the labial and palatal curvature points of the tooth root.

Periapical radiography

Periapical film is commonly used in root canal treatment and is also a frequent technique in orthodontic treatment to evaluate root resorption. The periapical film shooting method is divided into the bisecting-angle technique and distant paralleling technique. The bisecting-angle technique often fails to reflect the true length of the tooth due to the difficulty in accurately determining the projection angle. Consequently, the distant paralleling technique is mostly used for periapical film shooting as it avoids distortion caused by the tilt of the artificial projection angle. This technique is also simple and inexpensive. However, periapical film provides a limited field of view and is mostly used to examine subtle images of the root of individual teeth. Sha et al. found that when the X-ray deviated 10° from the ideal shooting angle horizontally or vertically, it was sufficient to cause misjudgment of root resorption. Kreich et al. employed registration and subtraction of radiographic images to quantify apical root resorption in maxillary permanent teeth after orthodontic treatment and assessed whether EARR occurred (Figures 2A, 2B, and 2C). The EARR was quantified using computed techniques, and tooth length (Figure 2D) was measured using Image J software to describe EARR in terms of pixels and relative root resorption (%). This method can quantify small changes associated with EARR *in vivo* (as reflected by changes as small as 0.6 pixels), facilitating early diagnosis of root resorption [3-5].

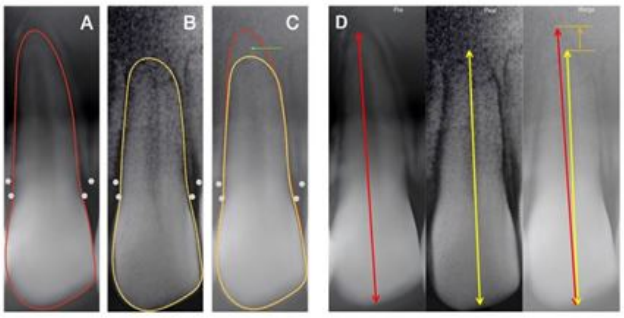


Figure 2: The same reference points were marked in the pretreatment (A) and posttreatment (B) radiographs to overlap the images and generate the posterior registration of the image (C). The subtracted image (C) shows root resorption (green arrow). (D) External apical root resorption was evaluated by measuring the long axis of the maxillary permanent teeth using Image J before and after orthodontic treatment.

Panoramic radiography

Panoramic radiography presents images of the entire dentition and is often used to observe the relationship between the maxilla and mandible, as well as masses, trauma, inflammation, and other lesions along with the surrounding tissues. Compared to CBCT, it is easy to operate, time-saving, low-cost, and has a low radiation dose. However, due to its non-positioning shooting, it is difficult for technicians to ensure that the projection angle remains consistent across different time points, leading to differences in magnification. Additionally, changes in tooth position before and after orthodontic treatment can cause errors in tooth length measurement. Therefore, the distortion rate of tooth length measured by panoramic radiography should be fully considered in clinical applications. In addition, panoramic radiography can only reflect root resorption from the mesial and distal directions, not from the buccal and lingual directions, similar to the periapical film [6,7].

Flores-Mir et al., compared the accuracy and reliability of measuring tooth length using conventional and CBCT reconstructed panoramic radiographs. They found that traditional panoramic radiographs were relatively inaccurate compared to actual tooth lengths, overestimating tooth length by 29%. In contrast, CBCT-reconstructed panoramic radiographs underestimated tooth length by 4%. Sameshima et al., observed that determining the position of the CEJ in panoramic films is challenging, and using these films to measure EARR before and after orthodontic treatment might overestimate root loss by 20% or more. Periapical radiographs, on the other hand, were more accurate in reflecting root resorption. Thus, when comparing the two methods, periapical films can be used to detect and diagnose root resorption in a timely and accurate manner. Consequently, it is recommended that clinicians take periapical radiographs when a root resorption diagnosis is suspected [8].

To reduce the influence of different magnifications and the distortion rates of 2D imaging techniques on the measurement results, Some scholars measured the lengths of roots and crowns on panoramic radiographs and calculated the Root-Crown Ratio

(RCR) and the relative RCR (rRCR=RCRT1/RCRT0) of each tooth before (T0) and after (T1) orthodontic treatment. A decrease in rRCR indicates a reduction in root length during treatment; however, this method is slightly time-consuming. Some scholars used the correction factor (CF, the ratio of the pretreatment crown height and posttreatment crown height) to calculate EARR (EARR=Root length after treatment × CF-root length before treatment). This method can correct differences in image magnification or distortion between pretreatment and post-treatment radiographs. Changes in tooth length before and after orthodontic treatment in 2D imaging may also result from the inclination of the tooth in the sagittal direction. To ensure that the shortening of the length (ΔL) shown in the frontal plane was not due to changes in tooth inclination in the sagittal plane (Δδ), Savoldi et al., combined panoramic and lateral cephalometric radiographs and applied trigonometric correction. The following formula was used to adjust the values of pretreatment tooth lengths: Lpre (OPTpost)=Lpre (OPTpre)(1 ± CosΔδ). The use of trigonometric correction may reduce the limitations of 2D X-ray imaging, but further research is needed to assess its accuracy.

CBCT

CBCT has clear advantages, such as relatively low radiation dose, short scanning time, high resolution, and reliable diagnosis. The slanted root resorption that occurs on the root surface can only be assessed by tomography techniques, and CBCT can provide more effective and accurate information on root resorption. Alamadi et al., evaluated the accuracy of 2D (periapical radiographs and panoramic radiographs) and 3D (CBCT) radiographic techniques in measuring slanted root resorption using a histological gold standard and indicated that CBCT is the most accurate technique for measuring and evaluating slanted root resorption. Sherrard et al., found that the reliability and accuracy of the tooth length and root length measurements derived from CBCT scans are at least as accurate and reliable as those from periapical radiographs. Lagravere et al., believe that CBCT can be displayed in a 1:1 ratio with the entity, allowing for fairly accurate evaluation of both soft and hard tissues. CBCT measurements of root length on images from different machines using multiplanar reconstruction had good to excellent reliability and consistence. Therefore, CBCT images can be used in clinical practice to determine the length of teeth and the true length of roots [9].

The three-dimensional reconstruction function of MSCT can reproduce the hard tissue and anatomical structure of the tooth in a stereoscopic shape, overcoming the shortcomings of traditional X-ray, such as structural distortion and unclear images. However, the thinner the MSCT scanning layer, the higher the simultaneous radiation dose required to achieve high resolution, which increases the harm to the human body and limits its widespread application in oral clinics. Some scholars have compared the difference in the image quality of the maxilla between the CBCT machine and the 4-slice MSCT, and the results show that CBCT can provide more satisfactory images of hard tissue. The diagnostic accuracy of CBCT and 8-slice computed tomography *in vitro* for root resorption showed that the spatial resolution of CBCT for minor defects on the root surface was higher than that of 8-slice computed tomography. And the radiation dose of CBCT is significantly lower than that of MSCT.

In summary, the accuracies of the above methods for evaluating EARR by measuring root length are different. Periapical films more accurately reflect the true length of the tooth compared to panoramic radiography. CBCT is comparable to periapical films in terms of accuracy in measuring tooth length, and its three-dimensional stereoscopic imaging can assess areas of EARR that cannot be detected by two-dimensional imaging. However, the results measured with CBCT are not absolutely reliable. Apical bone abnormalities and non-closure of apical foramen can make it difficult to locate the apex, resulting in measurement errors. Therefore, clinicians should fully consider the condition of the root itself when measuring tooth length and should not overlook the influence of physiological wear of crowns before and after orthodontic treatments on the accuracy of measurements when using the cusps of the crowns as landmarks.

RESULTS AND DISCUSSION

Root surface area

Root Surface Area (RSA) is another method to evaluate EARR and can also indirectly reflect the size of the periodontal membrane area. It has been reported that RSA can be measured by periapical film, contact scanning, laser 3D scanning, and CT scanning; however, the accuracies of these methods are not consistent.

Periapical film

Estimation of RSA for a single tooth can be made directly by intraoral X-ray projection. Tian et al., used the X-ray bisecting-angle technique to take pictures of a single tooth before extraction and segmented the root by height (h). Assuming each segment is cylindrical (Figure 3A), the authors measured the diameter (di) of each root segment on the X-ray film and get the formula: RSA=$\sum\pi$hdi=$\pi\sum$hdi. When h is small enough, $\sum$hdi is the area S of the area circled by the curve on the X-ray film (Figure 3B). Therefore: RSA=πS. Although this method lacks accuracy, it is easy to use, readily accepted by patients, and applicable regardless of whether there are single or multiple roots. Therefore, dentists could use this as a primary method to evaluate EARR in clinical settings.

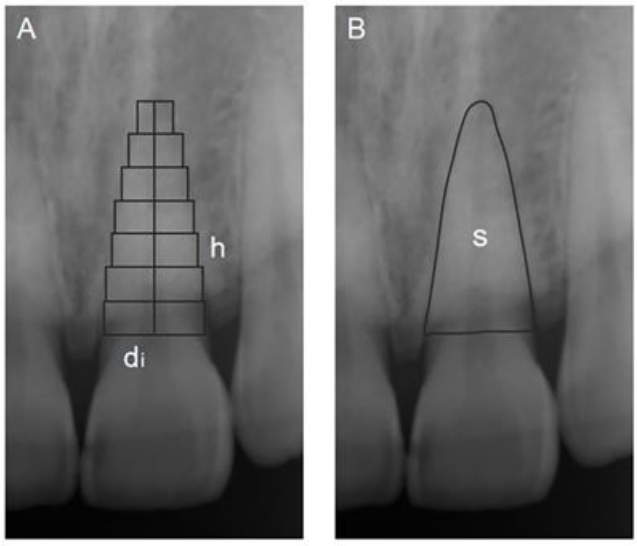


Figure 3: Estimation of the root surface area in the periapical film. (A) The root was divided into n parts, and each part was supposed to be a cylinder. The high of the cylinder is h, the diameter of the cylinder is di. (B) If h is small enough, ∑hdi=S, and RSA=πS.

Contact scanning and laser 3D scanning

Early contact scans involved placing the root on a metal nut, fixing it with wax, scanning the root contour with a three-dimensional contact probe, and inputting the measured data into Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) software to calculate RSA. However, this method required the root to be truncated, resulting in the loss of part of the root and inaccurate measurement results. With the development of laser technology, laser 3D scanning has become an accurate and reliable method for measuring RSA with high resolution. However, a disadvantage of laser 3D scanning is that it requires tooth extraction before measuring the RSA, as the root cannot be scanned directly inside the mouth. For teeth with multiple roots, indentation, or fused roots caused by mutual obstruction of the roots and variations on the surface of the roots, the accuracy of laser 3D scanning decreases, affecting the measurement results. Therefore, this method is rarely used in clinical practice.

With the widespread use of micro-Computed Tomography (micro-CT) and CBCT in tooth morphology research, some scholars have measured RSA by comparing optical scanning and CBCT three-dimensional scanning. Studies have shown that RSA measurement with CBCT is highly reliable and accurate. Gu et al., established a three-dimensional model of the tooth and pulp cavity by reconstructing three-dimensional images taken by micro-CT. They eliminated any cavities in the tooth model using the Boolean calculation method to unite the primary tooth model with the pulp cavity model, thereby removing the surface area of the pulp cavity inside the model. Subsequently, the model was smoothed, virtually cut along the CEJ, and divided into two parts: Crown and root. The overall surface area before cutting and the surface area of each part after cutting were then measured using Mimics software. Finally, the cross-sectional area (Ss) of the cutting surface was calculated using the formula Ss=(Sc+Sr-St)/2 (Figure 4), where Sc is the total area of the crown model after cutting, Sr is the total area of the root model after cutting, and St is the total area of the model before cutting. The RSA could then be indirectly calculated using Sr-Ss. Most of the noise, with dimensions significantly smaller than the dental features, could be filtered by performing a smoothing operation in Mimics. After obtaining the external surface area of the tooth model and the segmented parts, the remaining RSA corresponding to the periodontal ligament attachment layer at different levels could then be easily calculated. The model could theoretically be used to assess the RSA for each root of a multi-rooted molar or to simulate unequal attachment loss at various aspects of a tooth. Kerner et al., reported that the repeatability of Image J is good for both linear and surface area measurements in root coverage evaluation following periodontal plastic surgery, and it is used to measure RSA in related experiments.

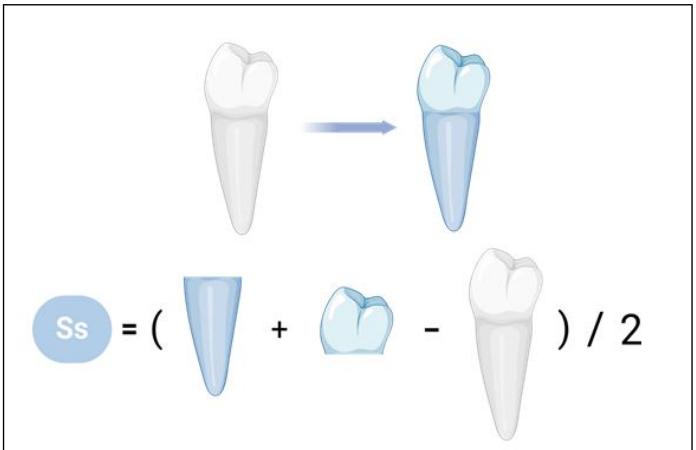


Figure 4: Schematic diagram of measurement and calculation of root surface area. The cutting plane line is aligned along the CEJ of a maxillary canine (Ss, the surface area of the cutting section; Sc, the surface area of the coronal portion; Sr, the surface area of the radicular portion; St, the surface area of the entire tooth).

In addition to the methods mentioned above, earlier literature also describes film-forming methods, photographic methods, and mass conversion methods, all of which have certain limitations. Methods like film formation, photography, mass conversion, contact scanning, and laser 3D scanning typically involve the use of extracted teeth when calculating RSA, making them difficult to apply in general clinical practice. However, three-dimensional CT scanning, particularly low-radiation, high-accuracy CBCT, offers a reliable method for measuring RSA in clinical settings.

Root volume

Regarding the measurement of root volume, micro-CT and CBCT are reliable methods for three-dimensional reconstruction, although there are also some differences between these two techniques.

Micro-CT: Micro-CT is known for its high accuracy and repeatability, allowing for precise root volume measurements through three-dimensional reconstruction. Sawicka et al., used

micro-CT to evaluate EARR after orthodontic treatment of premolars and found that Tview and CTan software can accurately measure the morphology of root resorption. Wierzbicki et al., developed a protocol to quantitatively evaluate Orthodontically Induced Tooth Root Resorption (OITRR) using micro-CT. They scanned the volume, number, and maximum depth of root resorption lacunae after orthodontic treatment and provided a method to predict further root resorption based on dentin demineralization. However, the dose and length of exposure of radiation are the limitations of this technology for patient applications. Currently, the *in vivo* analysis of dental tissues by micro-CT is possible only in laboratory animals because of the small diameter imager gantry restrictions; thus, the evaluation of root resorption in humans by micro-CT is currently only possible *in vitro*.

CBCT: CBCT has demonstrated high sensitivity and specificity for diagnosing EARR by assessing root volume. The voxel resolution of 0.3 mm is optimal for diagnosing root resorption, achieving high diagnostic performance while minimizing patient radiation exposure. Deliga et al., simulated EARR using cavities drilled with a round bur and compared the accuracy of digital periapical radiography and CBCT. They found CBCT to be superior, with a sensitivity of 89% for detecting EARR, compared to 68% for periapical radiographs. Additionally, CBCT outperformed panoramic radiography in detecting slight and severe resorption, though, its detection rate for moderate resorption was lower, possibly due to overestimation from the thin scanning layer and high resolution. Wang et al., used micro-CT as a reference standard to assess the accuracy of CBCT with a 125 μm voxel size in measuring the volume of simulated resorption cavities. They found CBCT to be accurate for cavities larger than 3.47 mm^3 but insufficient for those smaller than 1.07 mm^3, indicating that small volume changes might go undetected, leading to underestimation of root volume changes. In clinical applications, Wang et al. conducted a study involving CBCT scans before tooth extraction and micro-CT scans after tooth extraction in 27 teeth. They found that the accuracy of *in vivo* tooth volume measurement by CBCT matched that of *in vitro* measurements by micro-CT.

CBCT can be used to accurately reconstruct three-dimensional tooth models for linear, volumetric, and geometric measurements. Gao et al., performed three-dimensional reconstructions of target teeth by setting three orthogonal cross-sections (sagittal, coronal and transverse) and calculating the 3D model using Mimics software. The teeth were segmented at CEJ, and the root volume before and after orthodontic treatment was measured with 3D Properties software. Pereira et al. used CBCT images taken before orthodontic treatment (T_0) and immediately after tooth extraction space closure (T_1) to create a 3D surface model of the tooth at both time points. These models were superimposed and mapped to observe EARR, revealing a mild resorption trend with values lower than the accuracy threshold of tomography. To assess the common occurrence and amount of root resorption caused by orthodontic treatment, Chen et al., evaluated EARR in anterior teeth after miniscrew-assisted mass retraction in adult bimaxillary protrusion patients. CBCT data from before and after treatment were registered and 3D reconstructed with Mimics software. The root was divided into three vertical parts (cervical, middle, and apical) by two parallel planes perpendicular to the tooth axis. Each anterior tooth was further divided into four sectors (labial, palatal, mesial, and distal) by two perpendicular planes along the mesial-distal and labial-palatal directions (Figure 5). The change in root volume in these 12 parts was measured to determine root resorption. Chen et al., also used a similar method to further refine the resorption characteristics of each part. This method allows for the quick and accurate localization of EARR, providing a new clinical approach for identifying the precise areas and common occurrence rates of root resorption.

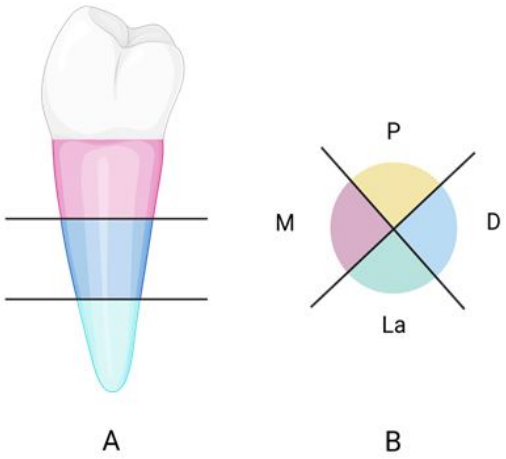


Figure 5: The segmentation of each tooth. (A) The root was vertically divided into three parts: cervical, middle, and apical. (B) Two perpendicular planes along the mesial-distal and labial-palatal directions divided each tooth into four sections.

Excessive orthodontic force, severe occlusal trauma, and periapical diseases can all lead to the occurrence of root resorption. Severe EARR severely affects the health and stability of teeth. Therefore, early identification of EARR is crucial. The disadvantages and advantages of these techniques and measuring methods mentioned above were summarized in Table 1.

Table 1: The disadvantages and advantages of the assessing method of EARR.

Methods	Advantages	Disadvantages	Indicator
Periapical radiography	Simple shooting method	Small imaging range	Root length
	Low radiation dose	Errors caused by angle changes	Root surface area

	1:1 image ratio	Overlapping anatomy	
	High diagnostic value for a single tooth		
Panoramic radiography	Simple shooting method	Image magnification and distortion	Root length
	Low radiation dose	Cannot show the three-dimensional relationships between structures	
	Wide imaging range		
	Easy to recognize anatomical markers		
CBCT	Low radiation dose than traditional CT	More radiation dose than periapical and panoramic radiography	Root length
	High spatial resolution	High cost	Root surface area
	Wide imaging range		Root volume
	1:1 image ratio		
	Clearly show the three-dimensional relationships between structures		
MSCT	High spatial resolution	High cost	Root volume
	Wide imaging range	High radiation dose	
	Show the three-dimensional relationships between structures		
Micro-CT	Higher spatial resolution than other methods	Long scan time	Root volume
		High cost	
		High radiation dose	
		Small imaging range	
		Extracted tooth	
Laser 3D scanning	Fast scanning speed	Extracted tooth	Root surface area
	High-precision 3D images		

Note: CBCT: Cone Beam Computed Tomography; MSCT: Multi-Slice Spiral Computed Tomography; Micro-CT: Micro-Computed Tomography

CONCLUSION

Apical radiography is reliable for preliminary screening of EARR or measuring root length on the same projective direction to evaluated the occurrence of EARR. However, in instances involving intricate cases or where there is a suspicion of a more severe form of EARR, CBCT is the preferred method for clinical diagnosis. Root length, root surface area, and root volume can also be used to evaluated EARR depending on specific requirements. In the future, with the continuous improvement of CBCT resolution and scanning speed, as well as the continuous combination with data analysis and artificial

intelligence, CBCT will better process and analyze image data and improve the diagnostic accuracy of EARR.

ACKNOWLEDGEMENTS

Not applicable.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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