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COMPARISON OF IMAGING METHODS FOR DETECTION OF SIMULATED HORIZONTAL AND OBLIQUE ROOT FRACTURES IN A NEW STUDY MODEL

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Abstract

This study aimed to compare the accuracy of standard, mesially shifted, and distally shifted periapical radiography with that of cone beam computed tomography (CBCT) in detecting oblique and horizontal root fractures. Nine teeth were randomly divided into the control, horizontal root fracture (HRF), and oblique root fracture (ORF) groups. Fractures were created without fragment separation using a perpendicular force and confirmed by transillumination. The imaging techniques included standard periapical radiography (SP), mesially shifted periapical radiography (MP), distally shifted periapical radiography (DP), and CBCT. Four postgraduate dental students evaluated the images for the presence or absence of fractures using a five-point scale. The sensitivity, specificity, accuracy, and area under the receiver operating characteristic (ROC) curve were calculated for each observer. CBCT demonstrated higher sensitivity and accuracy than radiographic methods. ROC curve values were significantly greater for CBCT than for MP (p=0.005). For horizontal fractures, the sensitivity (p=0.125), specificity (p=0.630), and accuracy (p=0.201) showed no significant differences; however, the ROC curve area (p=0.003), favored CBCT. The inter- and intraobserver agreements ranged from moderate to substantial (0.45–0.78). The study model effectively simulated challenging root fractures without fragment discontinuation, and CBCT performed significantly better in detecting oblique root fractures.

Keywords: Cone-Beam Computed Tomography. Diagnostic Imaging. Radiology. Root Fractures.

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1. Introduction

The majority of traumatic dental injuries (TDI) to the permanent dentition involve the anterior maxilla/anterior upper teeth and affect more than one billion people worldwide, making it an important public health problem (Kaur et al. 2018; Ferruzzi et al. 2021; Zaror et al. 2023). Root fracture is one of the most common TDI, representing 1.2%–7% of all injuries, and early detection is vital to prevent extensive damage to supporting tissues (Andreasen et al. 2018; Kapralous et al. 2020; Anantula et al. 2021).

The different types of root fractures make diagnosis difficult, especially in terms of the orientation of the fracture, whether oblique, vertical, or horizontal (Kobayashi et al. 2017; Andreasen et al. 2018; Kim et al. 2024). When this occurs, different radiographic techniques may be necessary, to achieve the best possible image to analyze the prognosis (Patel et al. 2021). In these cases, the diagnosis is made through clinical examination complemented by imaging examinations, such as periapical radiography (PR) and cone beam computed tomography (CBCT), which can confirm the fracture and visualize the tooth (crown and root) and adjacent alveolar bone (Sha et al. 2022; Alamri et al. 2023).

Conventional and digital intraoral radiography are the most common techniques used for tracing dental root fractures (Bueno et al. 2021; Andraws et al. 2022). However, these methods present two-dimensional images, resulting in the superimposition of anatomical structures (Almeida et al. 2016; Ghazizadeh et al. 2020; Kim et al. 2024). The X-ray beam must be parallel to the fracture plane for a root fracture to become visible on radiological examination (Ghazizadeh et al. 2020). Methods that vary the X-ray beam can be used to determine the presence of fractures (PradeepKumar et al. 2021; Kim et al. 2024). In contrast, CBCT is a three-dimensional exam that eliminates the superposition of maxillofacial structures, which allows better visualization and may help in the correct diagnosis of fractures (Almeida et al. 2016; Bueno et al. 2021).

In general, CBCT has proven to be better than periapical radiography for detecting external root resorption and root perforation (Patel et al. 2022; Pereira et al. 2024). However, previous studies have shown different results when comparing CBCT and periapical radiography in the diagnosis of root fractures (Kobayashi et al. 2017; de Lima et al. 2023). Most in vitro studies (Kobayashi et al. 2017; Andraws et al. 2020) have induced fractures through the separation and bonding of fragments, which improves visualization in imaging studies. However, the clinical reality is different because more irregular and thin lines of root fractures are commonly found, making visualization difficult with imaging methods. The proposed model in the present study simulates challenging fractures without fragment separation (Paz et al. 2022).

Clinical studies are the best option for evaluating the healing process involved in dental trauma (Mareque-Bueno et al. 2024) but are not always possible. Thus, in vitro studies are suitable alternatives for studying situations such as simulated root fractures (de Lima et al. 2023), and further investigation into the best imaging method in these cases is important. Therefore, the present in vitro study aimed to compare the accuracy of standard, mesially, and distally shifted periapical radiography and CBCT in the detection of oblique and horizontal root fractures in a new study model. The null hypothesis was that different radiographic techniques and fracture types do not influence the diagnosis of root fractures.

2. Material and Methods

To prepare the simulated root fracture model, sound bovine incisors were collected, cleaned, and stored in distilled water to maintain the humidity. Nine completely sound single-rooted teeth were selected and underwent careful clinical and radiographic inspection, to standardize for the absence of fractures, cracks, acutely curved roots, and relevant anatomical variations or physical defects. The root dimensions were measured using digital calipers (Mytutoyo, Tokyo, Japan). Initially, 30 teeth were selected; those that did not meet the inclusion criteria were excluded. Samples were randomly divided into three groups (n=3): the control (without fractures), horizontal root fracture (HRF), and oblique root fracture (ORF) groups.

To create a fracture line without fragment separation for the HRF and ORF groups, the teeth were stabilized, and a perpendicular force was applied using a hammer (Figure 1A). To confirm the discontinuity of the root and classify its orientation, all specimens were inspected using transillumination (Photonita, P1050, Florianópolis, SC, Brazil) (Valdivia et al. 2018). Specimens were imaged at 1.5x magnification (Nikon

D60 with a Nikkor 105 mm macro lens, Chiyoda, Tokyo, Japan), and the fracture lines were confirmed by a blinded evaluator (Figure 1B).

Each tooth was embedded in an artificially created model to simulate the anterior mandibular region. A red wax barrier (Wilson, Polidental Indústria e Comércio Ltda, Cotia, Brazil) was created around the human mandible, involving three dental alveoli: one central socket for the tooth to be analyzed and two adjacent sockets for sound teeth (Figure 1C). A vinyl polysiloxane impression material (Aerojet; São Paulo, Brazil) was prepared and inserted into the wax barrier. A mold was obtained, and melted wax was inserted into it (Figure 1D). All teeth were removed from the wax model, and an impression was made using vinyl polysiloxane material (Aerojet, São Paulo, Brazil) (Soares et al. 2011). The alveoli of the artificial model were individualized using bur #1516 (Edenta, São Paulo, Brazil) as handpieces, until the bovine teeth could be easily inserted into the sockets (Figure 1E). The pouring and curing procedures were repeated to produce nine standardized models (Paz et al. 2021).

To simulate the periodontal ligament, the roots were coated with melted wax (Epoxiglass, Diadema, São Paulo, Brazil) up to 2.0 mm below the cementum-enamel junction (CEJ), resulting in a 0.3 mm thick wax layer, to accommodate the space for a periodontal ligament (Soares et al. 2005) (Figure 1F). The models with artificial alveoli were filled with melted wax, and the teeth were inserted into the alveoli. Subsequently, the teeth were removed from the artificial alveoli, and wax was removed from the root surface. The periodontal ligament was simulated with a polyether impression material (Impregum F, 3M ESPE, St. Paul, MN, USA) that was placed in the root region. The tooth was then reinserted into the alveoli, and the excesses were removed with a scalpel blade (Soares et al. 2005; Soares et al. 2006) (Figures. 1G, H).

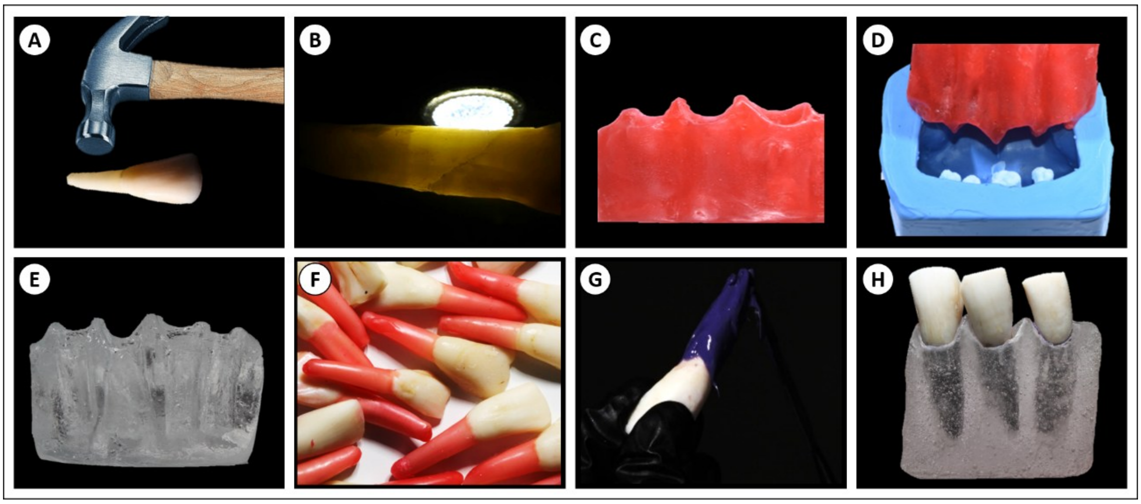

Figure 1. Images representing the study model. A) Root fracture without fragment separation produced with hammer; B) Root fracture assessment and classification by transillumination; C, D, E) Artificially created model; F) Roots coated with melted wax; G) Periodontal ligament simulation; H) Created model with three dental alveoli: one central socket for the tooth to be analysed (root fracture) and two adjacent sockets for sound teeth (control).

All models underwent four different imaging techniques: standard periapical radiography (SP); mesially shifted periapical radiography (MP); distally shifted periapical radiography (DP), and CBCT.

The digital intraoral periapical radiographs were acquired using a VistaScan Mini Plus® photostimulable phosphor (PSP) system (Dürr Dental, Bietigheim-Bissingen, Germany). An acrylic device was manufactured to promote the stabilization of the model, ensure the proximity and correct parallel relation of the PSP plate with the model, and guide the perpendicular incidence of the X-ray beam (Figure 2A). Exposures at mesial and distal angulations were obtained by shifting the cylinder horizontally by twenty degrees (Figure 2B–D). A Timex 70E x-ray unit (Gnatus, Ribeirão Preto, SP) was used, operating at 70 kV, 7 mA, exposure time of 0.2 s, and 35 cm focus/film distance. CBCT images were acquired using a Gendex CB-500 unit (Gendex Dental Systems, Hatfield, PA, USA) and the following parameters: 120 kV, 5 mA, 8x8, 5 cm FOV, and 0.2 mm voxel size.

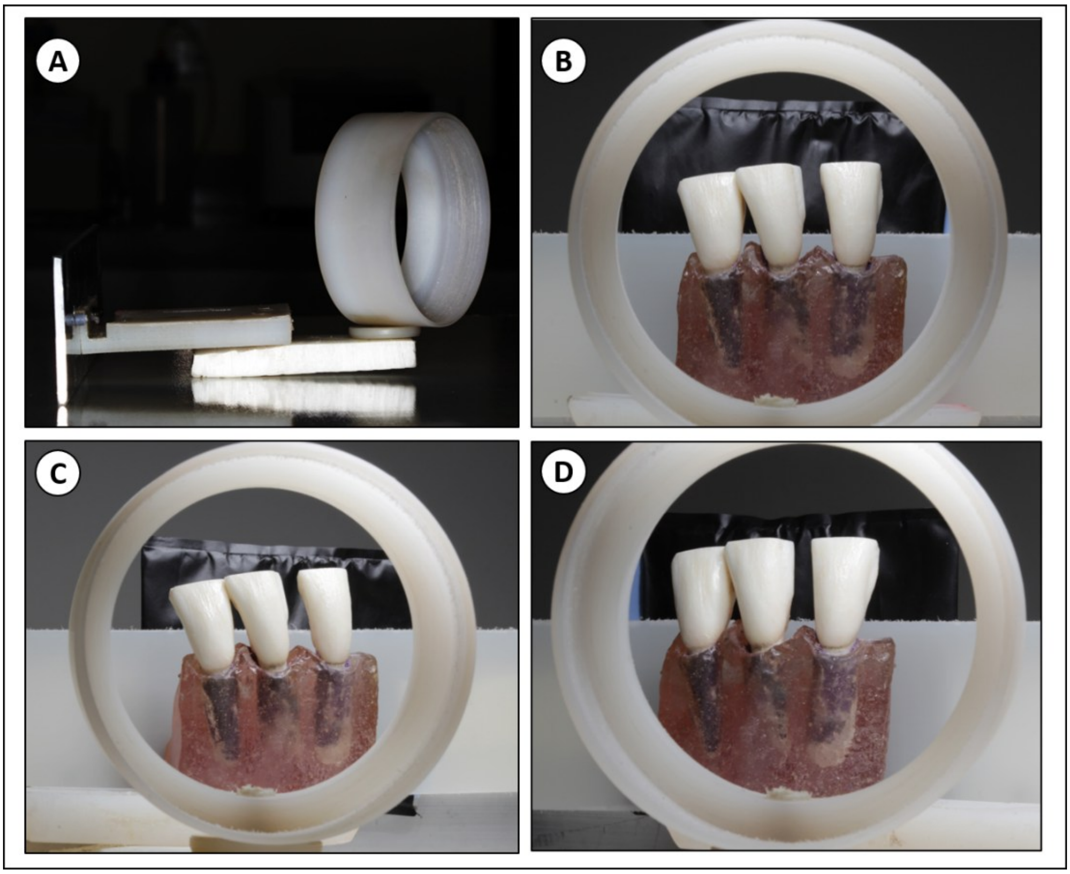

Figure 2. Acquisition of digital periapical radiographs. A) Acrylic device created to promote the stabilization of the model and guide the perpendicular incidence of the x-ray beam. B) Standard periapical radiography; C) Mesially shifted periapical radiography; D) Distally shifted periapical radiography.

All images were randomized using random.org (Randomness and Integrity Services Ltd., Dublin, Ireland) and assessed in blocks of 10 images by observers in a secluded, dimly lit room at three different times, to avoid eye fatigue. The radiographs in TIFF format were assessed in the Windows default photo viewer, and the DICOM files from CBCT images were evaluated using CS3D Imaging software (version 7; Carestream Health, Rochester, NY, USA) in the multiplanar reconstruction view (axial, coronal, and sagittal reconstructions). The images were analyzed on a Notebook HP Intel® Core™ 14" (Hewlett-Packard Company, USA) workstation. The observers were allowed to use tools for zooming, brightness, and contrast adjustment.

This study was approved by the ethics committee of the Federal University of Uberlandia (protocol #1.516.162). All images were analyzed in a blind experiment by four experienced specialists who were postgraduate dental students from orthodontics (n=1), oral radiology (n=1), and oral and maxillofacial surgery and traumatology (n=2). All examiners received training during the calibration session, and the criteria for detecting root fractures were clearly defined. The observers were instructed to analyze the central tooth of the model in relation to the presence or absence of a root fracture using a five-point scale, as follows: 1 point, definitely not present; 2 points, probably not present; 3 points, uncertain whether present or not; 4 points, probably present; and 5 points, definitely present. After 30 days, 35% of the samples were reevaluated under the same conditions, to assess the intraobserver reproducibility.

Statistical Analysis

To determine and compare the performance of digital radiography and CBCT, the sensitivity, specificity, accuracy, and area under the receiver operating characteristic (ROC) curve were independently calculated for each imaging modality using a website developed by Eng J. (2014). The results were compared by a one-way analysis of variance (ANOVA) with Tukey's post-hoc test, using BioEstat software (version 5.0; NGO Mamiraua, Belém, PA, Brazil), with a significance level of $p<0.05$.

The intra- and interobserver reproducibility was assessed using the kappa statistic and interpreted according to Landis and Koch (1977), as follows: 0.00–0.20, poor agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80 substantial agreement; and 0.81–1.00, almost perfect agreement. The tests were performed using MedCalc Statistical Software (version 15.2; MedCalc Software, Ostend, Belgium).

3. Results

The average sensitivity, specificity, accuracy, and area under the ROC curve for the imaging modalities are shown in Tables 1 and 2 for oblique and horizontal root fractures, respectively. Digital images of horizontal and oblique fractures on periapical radiography and CBCT are shown in Figures 3 and 4, respectively.

The sensitivity for the diagnosis of oblique root fractures was significantly higher for CBCT (p=0.015) than for MP and SP. The sensitivity was not significantly different among MP, SP, and DP. No significant differences in specificity were observed among MP, SP, DP, and CBCT (p=0.630). CBCT had higher accuracy than MP and DP. The accuracies of MP, SP, and DP were not significantly different (p= 0.015). CBCT had a significantly higher area under the ROC curve than MP (p= 0.005).

For horizontal fractures, no statistically significant differences in sensitivity (p=0.125), specificity (p=0.630), or accuracy (p=0.201) were observed. However, CBCT had a significantly lower area under the ROC curve (p=0.003) compared to SP, MP, and DP. No significant differences in the ROC curve were observed among MP, SP, or DP.

Table 1. Mean diagnostic values for oblique fractures using different imaging methods

	Sensitivity	Specificity	Accuracy	Area under ROC curve
Standard Periapical Radiography	25.0^{A}	83.3^{A}	54.2^{AB}	0.62^{AB}
Mesially Shifted Radiography	25.0^{A}	58.3^{A}	41.7^{A}	0.37^{A}
Distally Shifted Radiography	33.3^{AB}	58.3^{A}	45.8^{A}	0.56^{AB}
Cone Beam Computed Tomography	83.3^{B}	75.0^{A}	79.2^{B}	0.81^{B}

Different letters indicate significant differences, according to Tukey's post-hoc test (p<0.05).

Table 2. Mean diagnostic values for horizontal fractures using different imaging methods

	Sensitivity	Specificity	Accuracy	Area under ROC curve
Standard Periapical Radiography	100.0^{A}	83.3^{A}	91.7^{A}	0,.986^{A}
Mesially Shifted Radiography	83.3^{A}	58.3^{A}	70.8^{A}	0.858^{A}
Distally Shifted Radiography	91.7^{A}	58.3^{A}	75.0^{A}	0.948^{A}
Cone Beam Computed Tomography	66.7^{A}	75.0^{A}	70.8^{A}	0.681^{B}

Different letters indicate significant differences, according to Tukey's post-hoc test (p<0.05).

The kappa test results for observer reproducibility are presented in Table 3. Based on the Landis and Koch (1977) classification, the intra- and interobserver agreements were both moderate to substantial (0.60–0.78 and 0.45–0.69, respectively).

Table 3. Intra- and interobserver agreement kappa values, regardless of the fracture type or radiographic modality.

Reproducibility	Observer	Kappa value	Agreement
Intra-observer	1	0.605	Moderate
	2	0.700	Substantial
	3	0.605	Moderate
	4	0.787	Substantial
Inter-observer	1 vs. 2	0.461	Moderate
	1 vs. 3	0.618	Substantial
	1 vs. 4	0.455	Moderate
	2 vs. 3	0.620	Substantial
	2 vs. 4	0.695	Substantial
	3 vs. 4	0.540	Moderate

Observer 1: Oral and maxillofacial; Observer 2: Orthodontist; Observer 3: Oral and maxillofacial; Observer 4: Oral radiologist

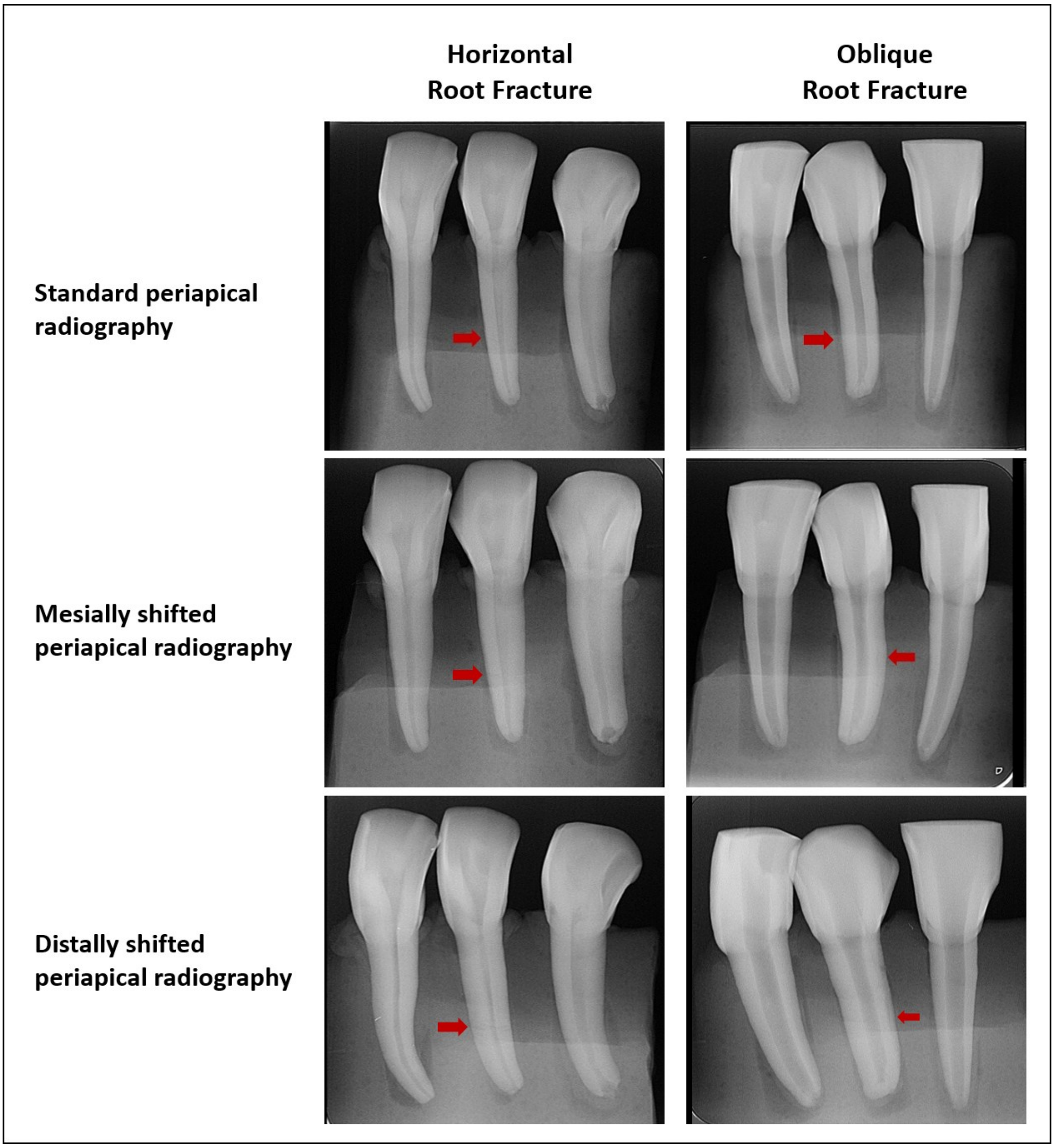

Figure 3. Digital periapical radiographs of horizontal and oblique root fractures in different imaging techniques. Standard periapical radiography, Mesially shifted periapical radiography, distally shifted periapical radiography. The red arrows indicate the fracture lines.

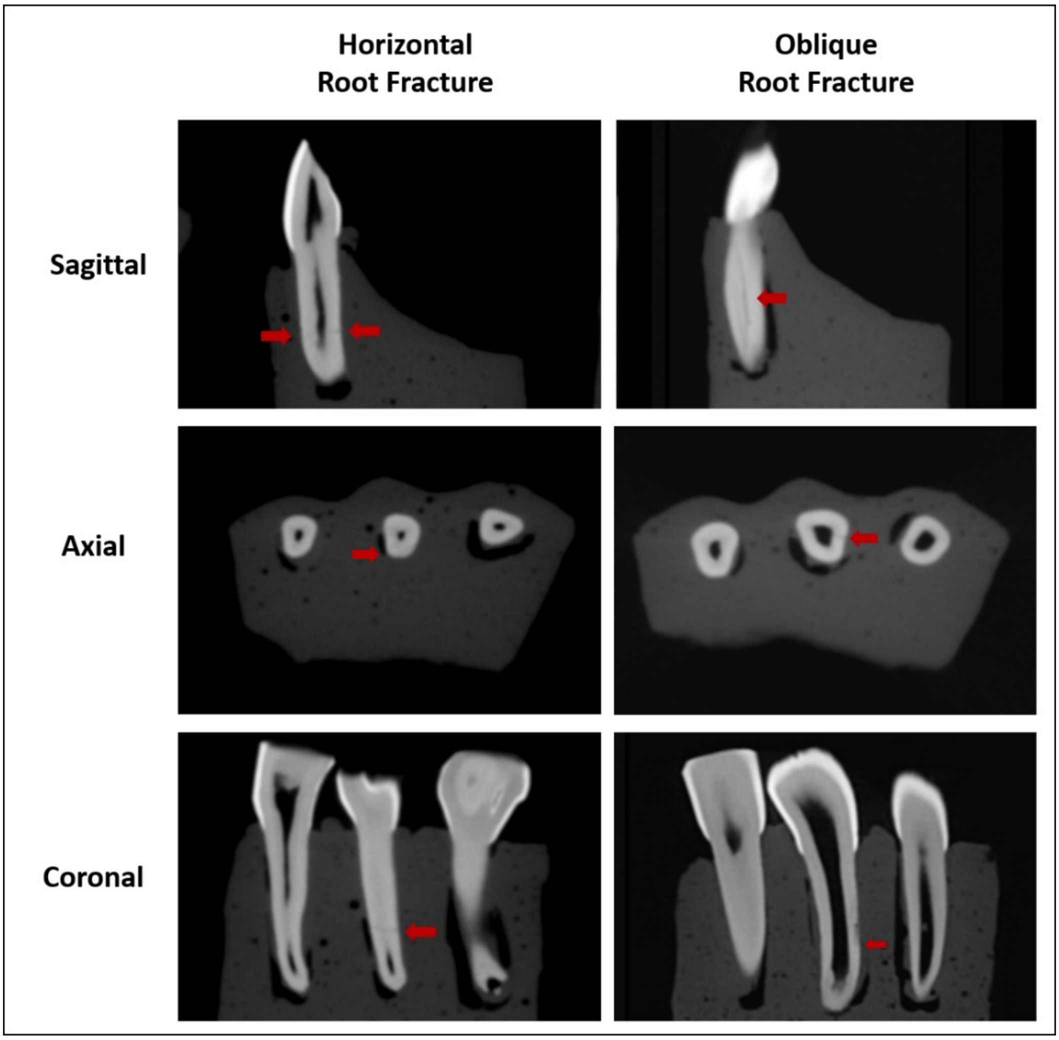

Figure 4. Cone-beam computed tomography images (CBCT) of horizontal and oblique root fractures. CBCT sagittal, axial and coronal views. The red arrows indicate the fracture lines.

4. Discussion

In this study, we investigated the effects of different digital imaging methods on the diagnosis of oblique and horizontal fractures, and researchers with different areas of expertise evaluated the images. Root fractures were selected for investigation because they have been the subject of numerous diagnostic accuracy studies with a wide range of study models and root fracture inductions. The sensitivity values were significantly higher for CBCT (p=0.015) for the diagnosis of oblique root fractures, rejecting the null hypothesis that different radiographic techniques and fracture types do not influence the diagnosis of root fractures.

Some parameters were evaluated in the samples to determine the best examination method for the diagnosis of root fractures. The results for sensitivity were represented as true positives, specificity as true negatives, accuracy as the total number of true positives and true negatives, and the area under the ROC curve as the relationship between the sensitivity and specificity of a diagnostic test. In this study, the sensitivity values were the most appropriate parameters.

Two-dimensional intraoral radiography is the most common tool for recognizing root fractures, owing to its low cost, convenience, and good resolution. Different techniques and angulations can be used for diagnosis (Ghazizadeh et al. 2020; Habibzadeh et al. 2023). Curiously, no significant differences were observed between MP, SP, DP, which may be related to the experience of the observers, who were all experienced specialists who use imaging exams in their clinical practice. Furthermore, the kappa scores obtained in this study indicated a moderate-to-substantial agreement regarding intra- and inter-observer reproducibility, with higher intra-observer agreement values for the oral radiology specialist.

Factors, such as age, experience, and training, may influence the results. Greater clinical experience may contribute to a better diagnosis of root fractures (Paz et al. 2022; Andraws et al. 2022). A previous study by our research group evaluated the diagnostic ability of undergraduate dental students to detect root fractures using different imaging techniques. Students showed a limited capacity to diagnose root fractures, with poor-to-good performance for the diagnosis of horizontal and oblique root fractures (Paz et al. 2022). In addition, better results have been obtained with CBCT examinations (Mareque-Bueno et al. 2024).

Detecting root fractures can be particularly difficult when the anatomical structures overlap on periapical radiographs. To improve visualization, it is crucial for the X-ray beam to align with the fracture plane; any misalignment may cause the fracture to be overlooked. To mitigate this challenge, acquiring two or three radiographs from different angles is recommended. This approach enhances fracture line visibility and significantly increases the diagnostic accuracy. Although periapical radiographs are widely used in clinical practice, combining multiple angles is essential to reduce the impact of anatomical overlap and ensure a more accurate diagnosis (Avsever et al. 2014; Paz et al. 2022).

The superior performance of periapical radiographs in detecting horizontal fractures, as demonstrated in this study, could be attributed to the clearer visibility of horizontal fractures when the X-ray beam is perpendicular to the fracture line. This positioning minimizes the anatomical overlap, making the fracture line more discernible. In contrast, the three-dimensional nature of oblique fractures complicates their detection, because multiple projections are often required for an accurate diagnosis. This distinction further emphasizes the importance of understanding the fracture orientation and selecting the most appropriate imaging technique for each clinical scenario (Kapralous et al. 2020; Lima et al. 2022).

CBCT should be considered an alternative to conventional radiography for the diagnosis of root fractures (Gao et al. 2021). Higher accuracy values have been reported for CBCT than for MP and DP, supporting the findings of several in vitro and in vivo studies (Al Hadi et al. 2020; Sha et al. 2022; Yang et al. 2023). However, CBCT has the disadvantages of higher radiation dose exposure and cost, compared with two-dimensional imaging, which may limit its use as a primary diagnostic method. CBCT remains a valuable alternative when periapical radiographs fail to reveal a fracture line; however, the patient may present with symptoms indicating root and/or alveolar fractures (Kobayashi et al. 2017; Kim et al. 2024).

To simulate the clinical situation, each experimental tooth used in the present study was fractured by a force applied by a hammer, similar to the method used in other studies (da Silveira et al. 2013; Avsever et al. 2014), to create an irregular line without fragment displacement and better simulate typical clinical conditions. Some studies have induced root fracture sectioning of the tooth using diamond discs (Paz et al. 2022) in an impact machine (Andraws et al. 2020), which results in wide and regular fractures that differ from those found in clinical practice. Clinical and radiographic diagnostics of dental root fractures are difficult because of challenges in diagnosis and tracing on intraoral radiographs, particularly when there are no well-defined fractures with fragment separation (Gao et al. 2021; Liao et al. 2021).

One limitation of this study was the use of a hammer to induce fractures, which may have resulted in variations in the applied force. To minimize this limitation, a strict protocol was followed in which the force application was controlled and performed by a single operator, with fractures induced at standardized points on the roots. This procedure was carefully designed to prevent fragment separation and to replicate real-world clinical conditions. Although variability in the application of force may influence the results, the methodology employed was validated in an earlier study, demonstrating its effectiveness in generating reproducible and representative fractures (Paz et al. 2022). Therefore, despite the inherent limitations of this method, its reproducibility supports its use in simulating dental fractures.

In the present study, we minimized the variability in the study conditions and attempted to mimic the clinical situation (Paz et al. 2020). It is important to ensure that the study models adequately reproduce the clinical situation (Andraws et al. 2020). In our study, we used an artificially created model to simulate the mandible and periodontal ligament of the tooth (Soares et al. 2005; Soares et al. 2006; Paz et al. 2021; Paz et al. 2022). However, the model design may change the image quality, depending on the quantity and type of material through which the X-ray beam passes. This may influence the diagnostic accuracy and is a limiting factor in this type of study (Andraws et al. 2020). Although this study aimed to diagnose root fractures using different radiographic techniques, this question is relevant to other in vitro studies on diagnostic accuracy. Another limitation was that radiographic examinations should be evaluated together with patient history and clinical examinations, to achieve an appropriate diagnosis. Thus, the study model was effective in simulating challenging root fractures without discontinuation of fragments. Computed tomography can better detect oblique root fractures, and the experience of the observer most likely contributed to better image interpretation.

5. Conclusions

The model effectively simulated complex root fractures while preserving fragment continuity. CBCT demonstrated superior performance in detecting oblique root fractures, showing significantly greater sensitivity and accuracy than digital periapical radiographs. In addition, CBCT achieved a notably high area under the ROC curve, reinforcing its enhanced diagnostic efficacy for these types of fractures.

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Ethics Approval: Not applicable.

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References

ALAMRI, H. M. et al. Detecting vertical root fractures using modified methylene blue dye: a preliminary in vitro study. *Healthcare (Basel)*. 2023, **11**(4), 504. https://doi.org/10.3390/healthcare11040504

AL HADI, D. et al. Detection of vertical root fractures using three different imaging modalities: an in vitro study. *The Journal of Contemporary Dental Practice*. 2020, **21**(5), 549-553.

ALMEIDA, G. de A. et al. Cone-beam computed tomography evaluation of dentoskeletal effects produced by the bonded expander and hyrax: a pilot study. *Bioscience Journal*. 2016, **32**. https://doi.org/10.14393/BJ-v32n3a2016-32319

ANANTULA, K.; VANKAYALA, B.; YADAV, S. S. A three-dimensional finite element analysis of stress distribution in maxillary central incisor with a horizontal mid-root fracture after various management protocols. *Journal of Conservative Dentistry and Endodontics*. 2021, **24**(5), 470-474. https://doi.org/10.4103/jcd.jcd_410_21

ANDRAWS YALDA, F. et al. Determination of a cone-beam CT low-dose protocol for root fracture diagnosis in non-endodontically treated anterior maxillary teeth. *Dento Maxillo Facial Radiology*. 2022, **51**(2), 20210138. https://doi.org/10.1259/dmfr.20210138

ANDRAWS YALDA, F. et al. Does anthropomorphic model design in ex vivo studies affect diagnostic accuracy for dental root fracture using CBCT? *Dento Maxillo Facial Radiology*. 2020, **49**(7), 20200093. https://doi.org/10.1259/dmfr.20200093

ANDREASEN, F. M.; ANDREASEN, J. O.; and TSILINGARIDIS, G. *Textbook and Color Atlas of Traumatic Injuries to the Teeth*. **5th** ed. Oxford, UK: Wiley Blackwell. 2018, 377-412.

AVSEVER, H. et al. Comparison of intraoral radiography and cone-beam computed tomography for the detection of horizontal root fractures: an in vitro study. *Clinical Oral Investigations*. 2014, **18**(1), 285-292. https://doi.org/10.1007/s00784-013-0940-4

BUENO, M. R.; AZEVEDO, B. C.; ESTRELA, C. A critical review of the differential diagnosis of root fracture line in CBCT scans. *Brazilian Dental Journal*. 2021, **32**(5), 114-128. https://doi.org/10.1590/0103-6440202104742

DA SILVEIRA, P. F. et al. Detection of vertical root fractures by conventional radiographic examination and cone beam computed tomography - an in vitro analysis. *Dental Traumatology*. 2013, **29**(1), 41-46. https://doi.org/10.1111/j.1600-9657.2012.01126.x

DE LIMA, K. L. et al. Influence of the technical parameters of CBCT image acquisition on vertical root fracture diagnosis: a systematic review and meta-analysis. *Clinical Oral Investigations*. 2023, **27**(2), 433-474. https://doi.org/10.1007/s00784-022-04797-z

DE LIMA, K. L. et al. Impact of fracture line width on radiographic diagnosis of vertical root fractures: analysis of the generalized estimating equation model. Chinese Journal of Dental Research. 2022, **25**(3), 197-204. https://doi.org/10.3290/j.cjdr.b3317977

FERRUZZI, L.P.C., et al. Oral health-related quality of life of athletes with disabilities: a cross sectional study. *Bioscience Journal*. 2021, **37**, e37008. https://doi.org/10.14393/BJ-v37n0a2021-5366

GHAZIZADEH, M. et al. Accuracy of digital image enhancement in detection of vertical and horizontal root fractures. *Dental Research Journal*. 2020, **17**(4), 266-272. http://dx.doi.org/10.4103/1735-3327.292066

GAO, A.; CAO, D.; LIN, Z. Diagnosis of cracked teeth using cone-beam computed tomography: literature review and clinical experience. *Dento Maxillo Facial Radiology*. 2021, **50**(5), 20200407. https://doi.org/10.1259/dmfr.20200407

HABIBZADEH, S. et al. Diagnostic efficacy of cone-beam computed tomography for detection of vertical root fractures in endodontically treated teeth: a systematic review. *BMC Medical Imaging*. 2023, **23**(1), 68. https://doi.org/10.1186/s12880-023-01024-3

KAPRALOUS, V. et al. Digital subtraction radiography in detection of vertical root fractures: accuracy evaluation for root canal filling, fracture orientation and width variables. An ex-vivo study. *Clinical Oral Investigations*. 2020, **24**(10), 3671-3681. https://doi.org/10.1007/s00784-020-03245-0

KIM, K. H. et al. Developing evidence-based clinical imaging guidelines for the diagnosis of vertically fractured teeth. *Oral Radiology*. 2024, **40**(4), 471-483. https://doi.org/10.1007/s11282-024-00766-2

KOBAYASHI-VELASCO, S. et al. Diagnosis of alveolar and root fractures: an in vitro study comparing CBCT imaging with periapical radiographs. *Journal of Applied Oral Science.* 2017, **25**(2), 227-233. https://doi.org/10.1590/1678-77572016-0332

LANDIS, J. R.; KOCH, G. G. The measurement of observer agreement for categorical data. *Biometrics*. 1977, **33**(1), 159-174.

LIAO, W. C. et al. Vertical root fracture in non-endodontically and endodontically treated teeth: current understanding and future challenge. *Journal of Personalized Medicine*. 2021, **11**(12), 1375. https://doi.org/10.3390/jpm11121375

MAREQUE-BUENO, M. S. et al. A retrospective clinical study to compare the ability of cone-beam computed tomographic images and periapical radiographs to reveal cracked teeth, split teeth, and teeth with vertical root fractures. *The Journal of the American Dental Association*. 2024, **155**(7), 614-623.e2. https://doi.org/10.1016/j.adaj.2024.04.009

PATEL, S. et al. Diagnosis and management of traumatic dental injuries using intraoral radiography and cone-beam computed tomography: an in vivo investigation. *Journal of Endodontics*. 2021, **47**(6), 914-923. https://doi.org/10.1016/j.joen.2021.02.015

PATEL, S.; BHUVA, B.; BOSE, R. Present status and future directions: vertical root fractures in root filled teeth. *International Endodontic Journal*. 2022, **55**(3), 804-826. https://doi.org/10.1111/iej.13737

PAZ, J. L. C. et al. Dental undergraduate students' ability in the diagnosis of root fractures: comparative analysis of different imaging methods. *Journal of Dental Education*. 2022, **86**(2), 136-143. https://doi.org/10.1002/jdd.12798

PAZ, J. L. C. et al. Fractured alveolar process displacement evaluation: effect of the rigidity of wire-composite splints. *Dental Traumatology*. 2021, **37**(2), 247-255. https://doi.org/10.1111/edt.12616

PEREIRA, S. A. et al. 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. *Journal of Clinical Medicine*. 2024, **13**(5), 1248. https://doi.org/10.3390/jcm13051248

PRADEEPKUMAR, A. R. et al. Diagnosis of vertical root fractures by cone-beam computed tomography in root-filled teeth with confirmation by direct visualization: a systematic review and meta-analysis. *Journal of Endodontics*. 2021, **47**(8), 1198-1214. https://doi.org/10.1016/j.joen.2021.04.022

SHA, X. et al. Comparison between periapical radiography and cone beam computed tomography for the diagnosis of anterior maxillary trauma in children and adolescents. *Dental Traumatology*. 2022, **38**(1), 62-70. https://doi.org/10.1111/edt.12706

SOARES, C. J. et al. Influence of cavity preparation design on fracture resistance of posterior leucite-reinforced ceramic restorations. *The Journal of Prosthetic Dentistry*. 2006, **95**(6), 421-429. https://doi.org/10.1016/j.prosdent.2006.03.022

SOARES, C. J. et al. Influence of root embedment material and periodontal ligament simulation on fracture resistance tests. *Brazilian Oral Research*. 2005, **19**(1), 11-16. https://doi.org/10.1590/s1806-83242005000100003

SOARES, P. B. et al. Effect of bone loss simulation and periodontal splinting on bone strain: periodontal splints and bone strain. *Archives of Oral Biology*. 2011, **56**(11), 1373-1381. https://doi.org/10.1016/j.archoralbio.2011.04.002

VALDIVIA, A. D. C. M. et al. Biomechanical effect of ferrule on incisors restored with a fiberglass post and lithium-disilicate ceramic crown after thermal cycling and fatigue loading. *The Journal of Adhesive Dentistry*. 2018, **20**(2), 133-142. https://doi.org/10.3290/j.jad.a40305

YANG, P. et al. Detection of vertical root fractures by cone-beam computed tomography based on deep learning. *Dento Maxillo Facial Radiology*. 2023, **52**(3), 20220345. https://doi.org/10.1259/dmfr.20220345

ZAROR, C. et al. Emergency and sequelae management of traumatic dental injuries: a systematic survey of clinical practice guidelines. *BMC Oral Health*. 2023, **23**(1), 704. https://doi.org/10.1186/s12903-023-03409-w