RESEARCH ARTICLE

Differential diagnosis of vertical root fractures using reconstructed three-dimensional models of bone defects

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Objectives: The purpose of this study was to evaluate the accuracy of diagnosing vertical root fractures (VRFs) by comparing the volume of bone defects in VRFs with those in non-VRFs on reconstructed three-dimensional (3D) models (TDMs) using CBCT.

Methods: 32 maxillary pre-molars and anterior teeth with radiolucent areas were evaluated on pre-operative CBCT images. Of the 32 teeth, 16 had a fractured root (VRF group) and 16 had a non-fractured root (non-VRF group). The radiolucent area of each tooth was traced in each dimension [mesiodistal, buccolingual and horizontal (the apicoincisal aspect)] by two observers, and 3D images were reconstructed with the Amira[®] software (Visage Imaging Inc., Richmond, Australia). The volume, V , of the TDM was divided into the coronal side and the periapical side at the horizontal slice through the apical foramen, and v was defined as the volume of the coronal side. The values of v/V were calculated for all cases. The Mann–Whitney U test was used to compare values between the VRF group and the non-VRF group ($p < 0.05$). A receiver operating characteristic (ROC) curve was constructed to select the optimal cut-point.

Results: There was a statistically significant difference in the value of v/V between the two groups ($p < 0.05$). With a cut-point derived from the ROC curve, and the sensitivity, specificity and accuracy of predicting the VRFs were 1.00, 0.75 and 0.88, respectively.

Conclusions: Lesions resulting from VRFs can be distinguished from those of non-VRFs on 3D CBCT images with a high degree of accuracy, based on their different 3D shapes.

Dentomaxillofacial Radiology (2014) **43**, 20140256. doi: [10.1259/dmfr.20140256](https://doi.org/10.1259/dmfr.20140256)

Cite this article as: Komatsu K, Abe Y, Yoshioka T, Ishimura H, Ebihara A, Suda H. Differential diagnosis of vertical root fractures using reconstructed three-dimensional models of bone defects. *Dentomaxillofac Radiol* 2014; **43**: 20140256.

Keywords: cone beam computed tomography; tooth fracture; periapical periodontitis; three-dimensional imaging

Introduction

Vertical root fractures (VRFs) are most commonly associated with endodontically treated teeth, with an incidence varying from 3.7% to 30.8% in such teeth.^{1–4} In a 5-year follow-up study of non-surgical endodontically

treated teeth, a root fracture was an adverse event in 32.1% of cases, for which the elected treatment was extraction.⁵ Thus, VRF of endodontically treated teeth appears to be clinically significant.¹ Pain and swelling, the presence of an isolated deep periodontal pocket and a combination of periapical and lateral radiolucency associated with the root are considered pathognomonic for VRFs.⁶ However, the clinical signs, symptoms and radiographic appearance of VRFs frequently resemble endodontic failure or periodontal disease. Therefore, it is difficult to distinguish VRFs from non-VRFs.⁷

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This work was supported by Grants-in-Aid for Scientific Research (A; grant number 19209059) and (B; grant number 25293385-00) from the Japan Society for the Promotion of Science, the Department of Pulp Biology and Endodontics, Division of Oral Health Sciences, Medical and Dental Sciences Track, Graduate School of Medical and Dental Sciences, Tokyo Medical and the Dental University, Japan.

Received 24 July 2014; revised 8 September 2014; accepted 16 September 2014

The diagnosis of a VRF is confirmed by the observation of a fracture line. It is difficult for clinicians to detect VRF using periapical radiographs, because the radiographic appearance differs depending on the stage of bone destruction, location of the fracture lines and positioning of the X-ray tube, tooth and detector. Moreover, radiographic signs are absent when the X-ray beam is not parallel to the plane of the fracture line. The superimposition of other structures often limits the sensitivity of radiographs for the detection of longitudinal fractures.⁸ One study reported that a fracture line was discernible only on periapical radiographs in 35.7% of cases (134 of 375 teeth).⁹ VRFs can generally be diagnosed only by observation of a fracture line with or without a surgical method.^{10–12} It would be advantageous to find more efficient methods for diagnosing VRF pre-operatively to avoid the cost and effort of unnecessary apical root resections.¹³

CBCT has become useful in various fields of dentistry, including endodontic surgery, and also in various endodontic diagnostic procedures, including the assessment of root fractures.⁸ Axial CBCT sections are ideal for the diagnosis of vertical fractures when the plane is perpendicular to the fracture line.¹³ However, limited studies exist regarding the value of CBCT in diagnosing root fractures. It is often difficult to detect root fracture lines using CBCT because detection is influenced by the orientation and width of the fracture.^{5,8} The presence of image artefacts resulting from radio-opaque materials, such as metals, gutta-percha and root canal sealers, decrease the accuracy of VRF detection using CBCT.^{14–17} A previous study evaluated the shapes of radiolucent areas on periapical radiographs of teeth with VRF and apical periodontitis.⁷ The shapes of the radiolucent areas on periapical radiographs of VRF teeth were found to be more complicated than those of non-VRF teeth in endodontically treated maxillary incisors and pre-molars. By evaluating the shapes of the radiolucent areas, a logistic regression equation was calculated to aid the diagnosis of VRF.

In a subsequent study, the logistic regression equation was calculated by evaluating the shapes of lesions of endodontically treated incisors and pre-molars on CBCT images parallel to the row of teeth and to the tooth axis.¹⁸ The results suggested that CBCT images may be better than periapical radiographs for distinguishing VRFs from non-VRFs. Typically, observers evaluate consecutive CBCT images in each section (mesiodistal, buccolingual and horizontal), meaning that CBCT images have only been evaluated using two-dimensional (2D) images. In this study, three-dimensional models (TDMs) were reconstructed from the mesiodistal, buccolingual and horizontal sections of CBCT images in VRF and non-VRF cases to compare the shape and volume of radiolucent areas.

The purpose of this study was to evaluate the accuracy of VRF diagnosis based on the shape and volume of bone defects in TDMs reconstructed from CBCT images.

Methods and Materials

This study was approved by the Ethics Committee of Tokyo Medical and Dental University, Tokyo, Japan (grant numbers 244 and 846).

The CBCT images obtained from patients who visited the Endodontic Clinic of Tokyo Medical and Dental University Hospital, Tokyo, Japan, from 2006 to 2013 and underwent surgical endodontic operations were retrospectively analysed.

The patients generally had teeth with clinical signs and symptoms, such as dull spontaneous pain, pain on percussion, occlusal pain, tenderness at the apical portion, the presence of a periodontal abscess and the presence of a sinus tract. The reasons why the teeth underwent surgical operations were as follows: incomplete healing of periapical lesions; prosthodontic reasons (long metal core, long bridge etc); and exploratory endodontic surgery for diagnosis of root fracture. All patients provided informed consent to undergo CBCT imaging and endodontic surgery.

The cases collected for this study were limited to endodontically treated maxillary pre-molars and anterior teeth. Teeth with two or more apical foramina, no localization within radiolucent areas, deep isolated periodontal pockets and bone defects judged as obvious VRFs from periapical radiographs were excluded.

The presence or absence of root fractures in each tooth was confirmed under an operating microscope (OPMI® Pico; Carl Zeiss, Jena, Germany) during a surgical procedure (Figure 1). Teeth that conformed to the criteria, with a fracture line observed during the surgical procedure, were categorized into the VRF group. Consequently, lesions from 16 teeth in 15 patients (3 males and 12 females; mean age, 53.4 years; age range, 32–79 years) were defined as the cases in this group, and evaluated in this study. As controls, lesions from 16 teeth in 16 patients (6 males and 10 females; mean age, 41.6 years; age range, 24–62 years) without a fracture line, which also fulfilled the criteria, were classified as the non-VRF group. These cases were randomly selected from cases that underwent apicoectomy.

For CBCT imaging, a FineCube system (Yoshida Dental Mfg. Co. Ltd, Tokyo, Japan) was employed in this study. Two types of field of view were available with this apparatus, that is, wide area mode (diameter, 81 mm; height, 75 mm) and high-resolution mode (diameter, 56 mm; height, 52 mm). The tube voltage and current were fixed at 90 kVp and 4 mA, respectively. For the scanning time, 19 or 37 s could be chosen. In each case, the field of view mode was decided by the dentists in attendance. If the wide area mode was selected, each image was reconstructed with $0.157 \times 0.157 \times 0.146$ -mm voxels. If the high-resolution mode was selected, each image was reconstructed with $0.108 \times 0.108 \times 0.10$ -mm voxels. The CBCT system was autocalibrated before each scanning procedure. Axial CBCT scans with a section thickness of 100–140 μ m were

Figure 1 Root fracture confirmed under an operating microscope.

pre-operatively obtained parallel to the occlusal plane. The CBCT images were retrospectively evaluated in three directions (mesiodistal, buccolingual and horizontal).

Two observers (KK and YA; dentists with 5 and 4 years' of experience, respectively) analysed all of the images separately to evaluate the interobserver agreement (KK1 and YA1). KK performed all of the measurements twice with a 1-year interval to evaluate the intraobserver agreement. Prior to this study, both observers were trained in the use of the software by evaluating the CBCT images of five teeth that were not included in the main study.

The radiolucent area was traced in each dimension by the observer using the Amira® v. 5.4.4 software (Visage Imaging, Richmond, Australia). In the evaluation of the horizontal image sections, the radiolucent area was traced using the Magic Wand tool in the Amira software, with the pixel value set within fixed limits (Figure 2). In each case, the pixel value was selected so that the tracings did not extend beyond the radiolucent areas in the

horizontal section. It was possible to draw the outline of each lesion semi-automatically. The periodontal ligament space and the root were not included in the lesion. In cases with cortical bone discontinuity around the lesion, a line was drawn to connect the edges of the damaged cortical bone. Tracing was performed directly using a touch-screen device (Wacom Co. Ltd, Saitama, Japan), and an accompanying pen was used to touch the touch-screen device with the Brush tool in the Amira software to obtain accurate shapes (Figure 3). The images evaluated in the horizontal sections were adjusted and modified in the mesiodistal and buccolingual sections (Figure 4). Representative images of VRF and non-VRF teeth are shown in Figures 5 and 6, respectively. The original CBCT digital imaging and communications in medicine view in multiple planes with the original volumetric view and the traditional 2D radiographic views of these images are shown in Figures 7 and 8, respectively.

Based on the lesion boundaries on the CBCT images, TDMs were reconstructed and their volumes were

Figure 2 Bone defect traced on a horizontal image.

Figure 3 In cases with discontinuous cortical bone around the lesion, a line was drawn to connect the edges of the damaged cortical bone, and the resulting bone defect was traced.

evaluated using the Material Statistics tool in the Amira software. The volume, V , of each TDM was calculated by multiplying the volume of a unit voxel by the number of voxels segmented. V was divided into two parts by the horizontal plane at the level of the apical foramen (Figure 9), and v represented the volume of the lesion on the coronal side of the division. Values of v/V were calculated in all cases. Statistical analyses were performed using SPSS® v. 17.0 (SPSS Inc., Chicago, IL). The Mann–Whitney U test was performed to compare v/V values between the VRF group and the non-VRF group at a significance level of $p < 0.05$. A receiver operating characteristic (ROC) curve was drawn by plotting the sensitivity against the false-positive rate ($1 - \text{specificity}$) over a range of cut-point values. As the cut-point shifts, the sensitivity increases and the specificity decreases, or *vice versa*.¹⁹ In this study, the optimal cut-point was selected to maximize the sum of the sensitivity and specificity.²⁰ Sensitivity, specificity, positive-predictive value and negative-predictive value (NPV) were calculated. Interobserver and intraobserver agreements were assessed using the kappa (k) statistic. Subsequent analyses were based on the values obtained by KK1.

Results

The median values of v/V in the VRF group and the non-VRF group were 0.89 and 0.42, respectively. There

Figure 4 Bone defects traced on buccolingual and mesiodistal images.

was a significant difference in the value of v/V between the two groups ($p = 0.0001$) (Figure 10).

The cut-point that provided the optimal probability of distinguishing VRF from non-VRF lesions was $v/V = 0.53$, which resulted in a total integrated area under the ROC curve of 0.91 (Figure 11).

Table 1 shows the prediction of VRFs and non-VRFs derived from this cut-point, where a sample with $v/V > 0.53$ was classified into the VRF group. All 16 of the true VRFs were predicted to be VRFs, whereas 12 of the 16 true non-VRF samples were accurately predicted.

With the cut-point derived from the ROC curve, the sensitivity, specificity and accuracy of predicting VRF were 1.00, 0.75 and 0.88, respectively. The positive-predictive value was 0.80 and the NPV was 1.0. The interobserver agreement (KK1 and YA1) computed by kappa analysis was 0.80, and the intraobserver agreement (KK1 and KK2) was 0.80 (Table 2). The strength of these agreements was satisfactory according to the interpretation category by Landis and Koch.²¹

Discussion

The present findings confirm the results of earlier research showing that radiolucent areas representing VRFs can be distinguished from non-VRF lesions by their shape and volume, specifically by the ratio of the volume coronal to the apical foramen to the entire volume.

In many studies, extracted teeth with root fractures or teeth with fractures confirmed by creating an endodontic access cavity were used. However, if the teeth

Figure 5 Representative three-dimensional image of a vertical root fracture. The red dot represents the apical foramen.

Figure 6 Representative case of non-vertical root fracture. The red dot represents the apical foramen.

were subjected to external force during the extraction or creation of an endodontic access cavity, they had the probability to crack at that time. Therefore, in this study, 16 VRF teeth confirmed during surgical operations were used. Moreover, in these cases, the VRFs could not be diagnosed before the surgical operation, but the fracture

line could be visualized during apicoectomy or exploratory endodontic surgery. This means that the diagnosis of the VRF in these cases was quite difficult.

In a previous study,⁷ two indices designated “complexity” and “radial SD” were measured by evaluating the shapes of the periapical radiolucent areas of endodontically

Figure 7 Representative original CBCT digital imaging and communications in medicine view in multiple planes with the original volumetric view and the traditional two-dimensional X-ray views of the vertical root fracture case shown in Figure 5. (a) Periapical radiograph showing a combination of periapical and lateral radiolucency associated with Tooth 11. (b-d) The radiolucent area was traced in each dimension: (b) horizontal, (c) buccolingual and (d) mesiodistal.

Figure 8 Representative original CBCT digital imaging and communications in medicine view in multiple planes with the original volumetric view and the traditional two-dimensional radiographic view of the non-vertical root fracture case shown in Figure 6. (a) Periapical radiograph showing an apical lesion associated with Tooth 8. (b–d) The radiolucent area was traced in each dimension: (b) horizontal, (c) buccolingual and (d) mesiodistal.

treated maxillary incisors and pre-molars on periapical radiographs. For both indices, the VRF group showed significantly greater values than those of the non-VRF group ($p < 0.05$). These findings indicate that VRF teeth have more complicated radiolucent areas than do non-VRF teeth. A multiple logistic regression analysis was

used to develop a predictive equation, and the probability of a VRF was calculated for all samples. A ROC curve was constructed to select the optimal cut-point. Each sample was predicted as VRF or non-VRF using this cut-point. With the cut-point derived from the ROC curve, the sensitivity, specificity and efficiency of predicting

Figure 9 The volume (V) of the three-dimensional model was separated into two parts by the horizontal plane at the level of the apical foramen. The red dot represents the apical foramen.

Figure 10 Values of v/V for the vertical root fracture (VRF) and non-VRF groups.

VRF were 0.68, 0.80 and 0.75, respectively. The total integrated area under the ROC curve was 0.75, which quantified the accuracy of the screening test in correctly distinguishing VRF from non-VRF.

However, periapical radiographs have disadvantages because they are 2D images, which often result in the overlapping of anatomical structures making it difficult to detect radiolucent areas precisely. Lesions confined within cancellous bones are often not visualized on periapical radiographs.²² These disadvantages may be improved by using CBCT because the ability to direct the X-ray beam from different angles allows for

reconstructed images in different planes (axial, coronal and sagittal).⁸ The capabilities of CBCT liberate the observer from the disadvantages of periapical radiography, namely the superimposition of structures in multiple planes.²³ A number of studies have reported that CBCT is more sensitive than periapical radiography in detecting apical periodontitis,^{24–29} and that CBCT can provide useful information for the diagnosis of VRF.³⁰

In another pilot study,¹⁸ the lesions of endodontically treated maxillary incisors and pre-molars on CBCT images taken parallel to the row of teeth and to the tooth axis were measured and evaluated using the above

Figure 11 Receiver operating characteristic (ROC) curve with a selected cut-point of 0.53. The ROC curve represents the probability levels. Sensitivity is plotted against (1 – specificity) for different possible cut-points. The total integrated area under the ROC curve was 0.91.

Table 1 Prediction of vertical root fractures (VRFs) and non-VRFs at a cut-point of 0.53

Correct label	Prediction		
	VRF	Non-VRF	Total
VRF	16 (100%)	0 (0%)	16 (100%)
Non-VRF	4 (25%)	12 (75%)	16 (100%)
Total	20	12	32

Samples with $v/V > 0.53$ were classified into the VRF group. The sensitivity and specificity for this cut-point were 1.00 and 0.75, respectively.

two indices from the previous study. VRF teeth had more complicated lesion areas than non-VRF teeth on CBCT. The multiple logistic regression analysis was used and a ROC curve was constructed to select the optimal cut-point. With the cut-point derived from the ROC curve, the sensitivity, specificity and overall accuracy of this logistic model for predicting VRF were 0.87, 0.89 and 0.88, respectively, and the total integrated area under the ROC curve was 0.93. These values were significantly greater than those obtained using periapical radiographs. Therefore, it is possible that CBCT is better than periapical radiographs for distinguishing VRFs from non-VRFs.

In our pilot study, the location of the apical foramen of 32 teeth was not identifiable with sufficient precision on periapical radiographs. Axial CBCT slices were able to show the root canal angles and define the location of the apical foramen.³¹ Additionally, the lesions of two cases in the VRF group in the present study were not detectable on periapical radiographs but were detected on CBCT images.

Observers typically evaluate consecutive CBCT images in each section (mesiodistal, buccolingual and horizontal), meaning that CBCT images have generally been evaluated using 2D images only. In this study, TDMs were reconstructed using mesiodistal, buccolingual and horizontal dimensions of CBCT images taken from VRF and non-VRF cases. TDMs enable us to understand the area of the lesion precisely. If these models are shown to patients, this will improve their understanding of their conditions. The results of this study need to be confirmed in a future prospective study with a control group and a blind analysis.

In this study, VRF lesions had a tendency to spread to the coronal portion because they occurred along the root fracture line. In some VRF cases, the radiolucent areas seemed to extend to crowding around the tooth root. Additionally, non-VRF lesions had a tendency to be spherical because they spread from the apical foramen. Therefore, the value of v/V in cases of VRF may

be close to one, while that in non-VRF cases may be closer to zero. In this study, there was a statistically significant difference in the value of v/V between the VRF group and the non-VRF group, indicating that the v/V value may be useful in diagnosing VRFs. The cut-point that provided the optimal probability of distinguishing VRF from non-VRF lesions was $v/V = 0.53$. An area of 1.0 signifies perfect accuracy, whereas an area of 0.5 represents random chance. Areas of < 0.5 indicate that the test is worse than random. Using the cut-point of 0.53, a sensitivity of one was obtained, meaning that 100% of the VRF cases were correctly diagnosed. Collectively, our method is more objective and may provide better predictions than those used in previous studies. The positive-predictive value, which is a good measure of how likely it is that a positive test ($v/V > 0.53$) will actually confirm the presence of a VRF, was high in this study. The NPV indicates the likelihood that a negative test result ($v/V < 0.53$) will actually confirm that the tooth does not have a VRF. The NPV was one in this study, indicating that this result was very reliable.

This study introduces an objective standard for diagnosing VRFs using CBCT. In this study, it was possible for the observers to draw the outline of each lesion semi-automatically using the Amira 5.4.4 software. However, observers need to be trained to use the system and the software for diagnosis. In this study, we found substantial degrees of interobserver and intraobserver agreement. However, in a few cases, a discrepancy in the outline of lesions was recognized, because of the presence of image artefacts resulting from metals, gutta-percha and root canal sealers. In three cases (two cases of VRF and one case of non-VRF), the diagnosis of VRF/non-VRF was not accurate, because it was considered that the horizontal plane at the level of the apical foramen obtained by KK1, KK2 and YA1 did not demonstrate concordance. The VRF is not diagnosed with radiographs alone, as clinical signs are also taken into consideration. However, it is often necessary to use CBCT because periapical radiographs are sometimes not able to detect a lesion. When the information is insufficient to diagnose VRF with periapical radiographs alone, CBCT often provides useful information on the shape and location of a radiolucent area and helps in diagnosis and treatment planning. However, the principle of keeping radiation exposure as low as reasonably achievable should always be considered.

In conclusion, because lesions resulting from VRFs have a different appearance on CBCT images compared with those resulting from non-VRFs, three-dimensional CBCT images can be used to distinguish the VRF with a high degree of accuracy.

Table 2 Kappa values for interobserver and intraobserver agreements

Agreement	Observer	Kappa value	95% confidence interval	Interpretation
Interobserver agreement	KK1 vs YA1	0.80	0.59–1.00	Substantial
Intraobserver agreement	KK1 vs KK2	0.80	0.59–1.00	Substantial

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