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Diagnostic accuracy of small volume cone beam computed tomography and intraoral periapical radiography for the detection of simulated external inflammatory root resorption

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Abstract

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Aim To compare in an *ex vivo* model the ability of digital intraoral radiography and cone beam computed tomography (CBCT) to detect simulated external inflammatory root resorption lesions, and to investigate the effect of altering the degree of rotation of the CBCT scanners X-ray source and imaging detector on the ability to detect the same lesions.

Methodology Small and large simulated external inflammatory resorption (EIR) lesions were created on the roots of 10 mandibular incisor teeth from three human mandibles. Small volume CBCT scans with 180° and 360° of X-ray source rotation and periapical radiographs, using a digital photostimulable phosphor plate system, were taken prior to and after the creation of the EIR lesions. The teeth were relocated in their original sockets during imaging. Receiver operator characteristic (ROC) analysis and kappa tests of the reproducibility of the imaging techniques were carried out and sensitivity, specificity, positive and negative predictive values (PPV and NPV) were also determined for each technique.

Results The overall area under the ROC curve (Az value) for intraoral radiography was 0.665, compared to Az values of 0.984 and 0.990 for 180° and 360° CBCT, respectively ($P < 0.001$). The sensitivity and specificity of 180° and 360° CBCT were significantly better than intraoral radiography ($P < 0.001$). CBCT, regardless of the degree of rotation, had superior NPVs ($P < 0.01$) and PPVs ($P < 0.001$) to periapical radiography. The intra- and inter-examiner agreement was significantly better for CBCT than it was for intraoral radiography ($P < 0.001$). The ability of small volume CBCT to detect simulated EIR was the same regardless of whether 180° or 360° scans were taken. Examiners were significantly better able to identify the exact location of the artificial resorption lesions with CBCT than they were with periapical radiographs ($P < 0.001$).

Conclusion CBCT is a reliable and valid method of detecting simulated EIR and performs significantly better than intraoral periapical radiography. Small volume CBCT operating with 360° of rotation of the X-ray source and detector is no better at detecting small, artificially created EIR cavities than the same device operating with 180° of rotation.

Keywords: cone beam computed tomography, diagnosis, external inflammatory resorption, periapical radiography.

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Introduction

Root resorption is the loss of dental hard tissue, namely cementum and dentine, as a result of odontoclastic cell action (Hammarström & Lindskog 1985). Root resorption may be simply classified by its location in relation to the surface of the root. Internal resorption occurs on the root canal wall whilst external resorption affects the roots outer surface (Tronstad 1988, Trope 2002). External root resorption is a common complication after severe dental luxation (Andreasen & Vestergaard Pedersen 1985) and avulsion (Andreasen & Hjørting-Hansen 1966a, b) injuries. Three main types of external resorption associated with dental traumatic injuries have been described: surface resorption, inflammatory resorption and replacement resorption (Andreasen & Hjørting-Hansen 1966a, b). The prevalence of external inflammatory resorption (EIR) following all types of luxation injury is approximately 4.9%. However, the frequency of EIR following intrusive luxation injuries alone is 38% (Andreasen & Vestergaard Pedersen 1985). EIR occurs in 30% of replanted, avulsed teeth (Andreasen *et al.* 1995a).

EIR is characterized radiographically by bowl shaped radiolucent lesions along the surface of the root, with radiolucencies in the adjacent alveolar bone (Andreasen & Hjørting-Hansen 1966a). EIR is dependent on the presence of infected necrotic tissue within the root canal space of the affected tooth for its development and progression (Andreasen & Hjørting-Hansen 1966b, Andreasen 1981). The process begins as surface resorption. In some instances, this normally transient event will expose underlying dentinal tubules, allowing bacterial toxins from within the root canal to penetrate through to the periodontal tissues. The toxins stimulate and intensify the resorption process ensuring its progression and the resorption proceeds towards the root canal space (Andreasen & Hjørting-Hansen 1966b, Andreasen 1981).

EIR may advance rapidly, such that an entire root may be resorbed within a few months (Andreasen & Andreasen 2007). Clinical treatment of EIR is based on the effective removal of the causal agent, i.e. the infected necrotic pulpal tissue in the root canal space. This will arrest the resorptive process, and create an environment conducive to hard tissue repair of the damaged root surface (Cvek 1973, 1992, Dumsha & Hovland 1995). It is therefore essential that root canal treatment is initiated as soon as radiographic signs of EIR are identified (Cvek 2007). The earlier the resorption is diagnosed and treated the better the prognosis is for the affected tooth. Failure to diagnose and treat the condition may result in tooth loss.

The diagnosis of EIR in clinical situations is usually based solely on the radiographic demonstration of the process (Andreasen *et al.* 1987). The initial radiographic signs of EIR can potentially be visualized as early as two weeks after replantation of avulsed teeth (Andreasen & Hjørting-Hansen 1966a). However, the limitations of conventional radiographic imaging in dentistry have been well reported on. The diagnostic yield of radiographs are reduced by adjacent anatomical interferences (Bender & Seltzer 1961, Revesz *et al.* 1974, Kundel & Revesz 1976, Gröndahl & Huumonen 2004), geometric distortion (Gröndahl & Huumonen 2004) and by the compression of three dimensional structures on to a two dimensional shadow-graph (Webber & Messura 1999, Cohenca *et al.* 2007, Patel *et al.* 2009a). These limitations may result in late diagnosis of EIR. Several studies have demonstrated that conventional intraoral radiography is not a reliable technique for detecting external root resorption in its early stages (Andreasen *et al.* 1987, Chapnick 1989, Goldberg *et al.* 1998). Computed tomography (CT) (Silveira *et al.* 2007) and cone beam computed tomography (CBCT) (Liedke *et al.* 2009) have demonstrated good diagnostic ability in the identification of simulated external resorption. Currently there is little published research directly comparing the diagnostic ability of CBCT and conventional intraoral radiography in this area.

The purpose of this study was to compare in an *ex vivo* model, the ability of digital intraoral radiography and CBCT to detect simulated external inflammatory root resorption lesions, and to investigate the effect of altering the degree of rotation of the CBCT scanners X-ray source and detector on the ability to detect the same lesions.

Materials and methods

Twelve mandibular incisor teeth in three partially dentate, intact, dry, human mandibles obtained from the anatomy department of King's College Dental Institute were used in this study. Prior to use, each mandible was soaked for 90 min in warm soapy water (Fairy Liquid Original, Procter and Gamble, Weybridge, UK). The mixture served to reduce the surface tension of the mandibles and increase their wetness and resilience preceding tooth extraction and radiological imaging. Intraoral periapical radiographs (Digora® Optime; Soredex, Tuusula, Finland) and CBCT (3D Accuitomo 80; J Morita, Kyoto, Japan) scans of the mandibular incisor teeth were then taken to identify any existing resorption or periapical disease associated with the teeth. A putty matrix (polyvinyl-siloxane

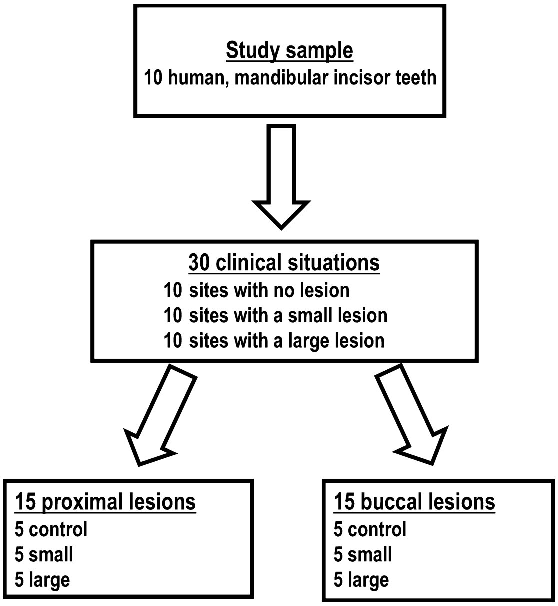

Figure 1 Flow chart demonstrating the allocation of the experimental teeth to their groups.

impression material, President, Coltène AG, Alstätten, Switzerland), encasing the incisal edges and the lingual aspects of the crowns of the incisor teeth, and extending to a level below the alveolar crest, was created for each mandible. This was used as a template to ensure complete reseating of the extracted teeth prior to further imaging. Each experimental tooth was then atraumatically extracted and examined under a dental operating microscope (3 step entreé Dental Microscope; Global, St Louis, MO, USA) to confirm the roots were intact and unaffected by any resorptive process. Two teeth on one mandible had damaged root surfaces and were eliminated from the study, reducing the subject material to 10 teeth.

The 10 teeth were randomly allocated to two groups, A and B. The five teeth in group A had simulated resorption cavities created on their buccal surfaces and the five teeth in group B had lesions created on a proximal surface (Fig. 1). The resorption cavities were machined equidistant between the crestal bone and the root apex, on the assigned root surface. Steel rose head burs (Henry Schein, Gillingham, UK) with diameters of 0.5 and 1.0 mm were selected to create simulated resorption cavities. Metal stops were laser welded around the circumference of the burs to create hemispherical cavities of 0.5 mm × 0.25 mm and 1 mm × 0.5 mm respectively. The lesions were created using an endodontic motor (X-SMART DUAL™, Dentsply, Addlestone, UK) set at 1000 rpm. A dental operating microscope was used to ensure accurate location of the cavities. Following the creation of 'small' lesions (0.5 mm × 0.25 mm), the teeth were relocated in the mandibles and digital periapical radiographs and CBCT scans of the lower anterior teeth were taken in an identical manner to the base line images (see Radiographic technique section) (Figs 2–4). The teeth were subsequently removed from their sockets again and the lesion dimensions were increased to the size of the 'large' cavities (1 mm × 0.5 mm). A final set of CBCT scans and periapical radiographs was then taken (Figs 5–7).

Radiographic technique

A digital photostimulable phosphor plate (PSP) system (Soredex) was used to capture the intraoral radiographic images. Intraoral radiographs were exposed with an X-ray unit (Heliodent, Sirona, Bensheim, Germany) operating at 65 kV and 7 mA. The exposure time was 0.16 s. Two specifically designed jigs were created to allow standardized reproducible radiographs and CBCT scans of the subject teeth to be taken. The jig used for the intraoral radiographs (Fig. 8) allowed the mandible and their teeth to be set at distance of 36.5 cm from the X-ray source. The mandibles could be removed and relocated on their own individual putty (Coltène AG) templates on top of a wooden disc. The thickness and distribution of the putty ensured that the teeth were perpendicular to the X-ray beam, producing parallel images. The disc could move on runners so that each tooth could be centred on the X-ray tube in turn. The disc rotated to allow a change in angulation of the teeth in relation to the X-ray source for parallax images. A mathematical protractor measured the angle between the teeth and the X-ray source. For parallel radiographs the teeth were aligned with the 90° line on the protractor, which was centred on the X-ray tube. For parallax images the disc was rotated, left and right so that 20° horizontal angles were created between the X-ray source and the tooth. The tube head was fixed in position during imaging by the wooden jig. A sheet of acrylic (Plexiglas®; Evonik Industries AG, Essen, Germany) 1 cm thick was placed between the X-ray tube and the mandible, prior to taking each radiograph, in order to recreate the soft tissue attenuation occurring clinically.

For the CBCT images a small volume scanner (J Morita) was used. A purpose built jig was constructed to position the mandibles correctly for the scans. The jig

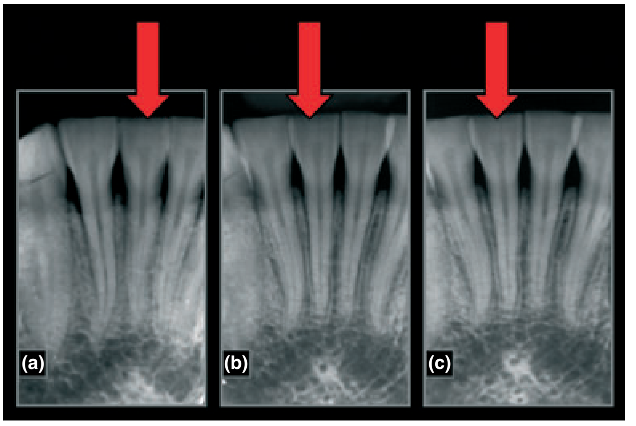

Figure 2 Parallel (b) and parallax (a and c), periapical radiographs of the lower right central incisor (indicated with red arrows), following creation of the 'small' simulated resorption cavity on the buccal surface of the root of the tooth. No such lesion is apparent on the radiographs.

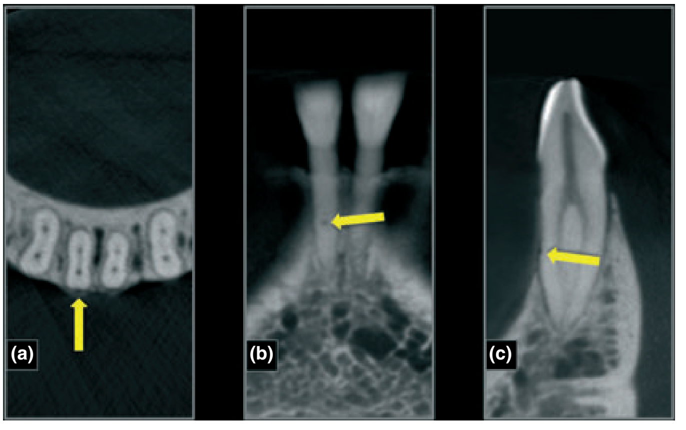

Figure 3 Axial (a), coronal (b) and sagittal (c) reconstructed 180° CBCT images of the lower right central incisor tooth following creation of the 'small' simulated resorption cavity on the buccal surface of the root. The artificial lesion (yellow arrows) can be identified on all of the reconstructed images.

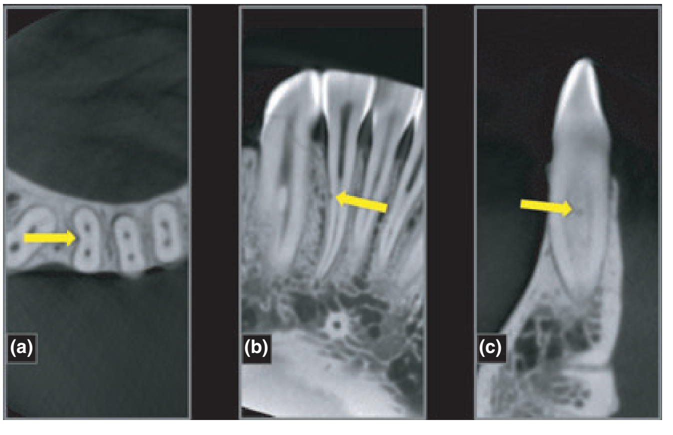

Figure 4 Axial (a), coronal (b) and sagittal (c) reconstructed 180° CBCT images of the lower right lateral incisor tooth following creation of the 'small' simulated resorption cavity on the distal surface of the root. The artificial lesion (yellow arrows) can be identified on all of the reconstructed images.

consisted of a plywood platform with a 2 cm length of dowel rod attached to the centre of its undersurface. When positioning the jig the scanners chin rest was removed and the jig was located in the vacated slot by means of the dowel attachment. The entire inferior border of each mandible was embedded in separate putty (Coltène AG) matrices, placed and allowed to set on specifically created grooves on the top of the platform. The thickness and distribution of the impression material in each matrix was such that the lower anterior teeth of each mandible were inclined with their long axes perpendicular to their supporting platform.

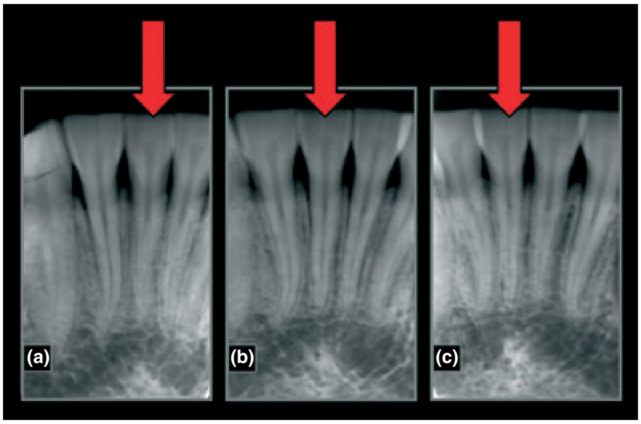

Figure 5 Parallel (b) and parallax (a and c) digital, periapical radiographs of the lower right central incisor (indicated with red arrows), following creation of the 'large' simulated resorption cavity on the buccal surface of the root of the tooth. The lesion cannot be identified on the radiographs.

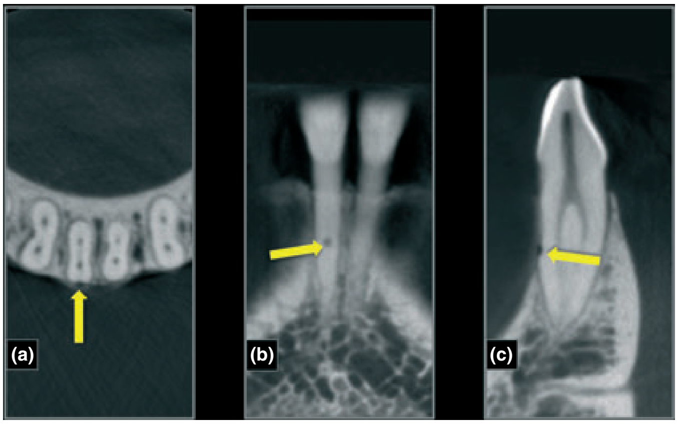

Figure 6 Axial (a), coronal (b) and sagittal (c) reconstructed, 180° CBCT images of the lower right central incisor tooth following creation of the 'large' simulated resorption lesion on the buccal surface of the root. The artificial lesion (yellow arrows) can be clearly identified on all of the reconstructed images.

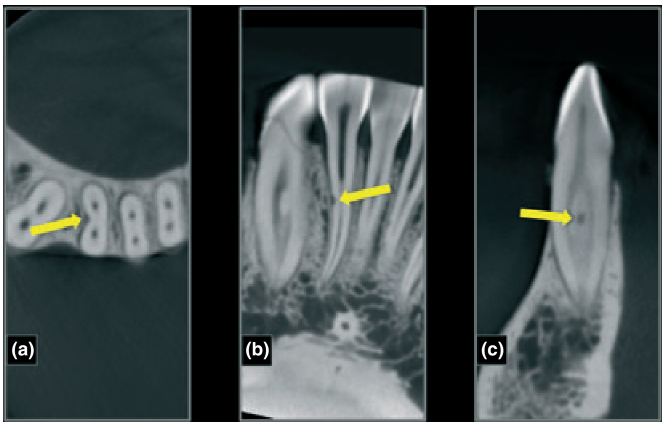

Figure 7 Axial (a), coronal (b) and sagittal (c) reconstructed 180° CBCT images of the lower right lateral incisor tooth following creation of the 'large' simulated resorption cavity on the distal surface of the root. The artificial lesion (yellow arrows) can be identified on all of the reconstructed images.

This reduced the amount of up-righting of the data which would be required using the software. Once the impression material had set the matrices could be removed and replaced on the platform ensuring reproducible and accurate relocation of each mandible on the jig for every scan. Prior to each scan, the acrylic sheet (Evonik) was secured over the X-ray source using sellotape (Henkel Consumer Adhesives, Winsford, UK) in order to attenuate the beam and replicate the soft tissue scatter encountered in a clinical setting. Exposure parameters of 90 kV, 3.0 mA and a 17.5 s scan were used for the CBCT scanner when capturing 360°

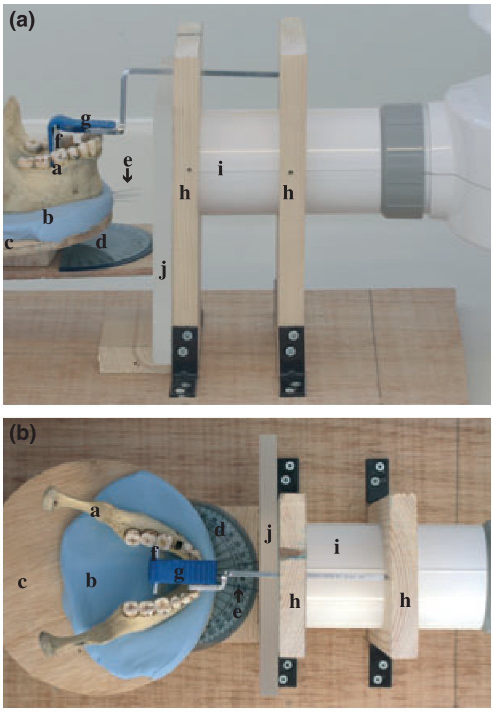

Figure 8. Mandibular specimen (a) embedded in its putty template (b) to facilitate its accurate relocation on the rotatable wooden disc (c). The angle between the X-ray beam and the tooth being imaged is measured by a mathematical protractor (d) fixed in position in relation to the disc. Stainless steel wire pointers (e) centred on and perpendicular to the long axis of each incisor are embedded in the putty and hover over the protractor to ensure accurate measurement of the angle between the teeth and the X-ray beam. The phosphor plate (f) is set in position by a standard anterior intra-oral film holder (g) which is fixed in a wooden jig (h) designed to ensure exact positioning of the X-ray tube (i). The acrylic soft tissue equivalent (j) is securely positioned between the X-ray source and the mandible.

images. The scans exposure time was reduced to 9 s for the 180° scans. All CBCT data were resliced to produce 0.16 mm slice intervals and 1.2 mm slice thickness. The brightness and contrast of all images were optimized to allow the best possible visualization of the lesions.

Radiological assessment

Eight examiners, comprising three endodontists (n = 3) and five endodontic postgraduates (n = 5) assessed the radiographs and CBCT scans in the following sequence over four sessions: session 1 – radiograph examination, session 2 – CBCT 180° and 360° examination, session 3 – repeat radiographs and session 4 – repeat CBCT scans. The repeat sessions (sessions 3 and 4) were carried out to assess intra-examiner agreement. In sessions 3 and 4, half of the original images were re-randomized and shown to the examiners again. There was at least one week between each session. The radiographs, the 180° CBCT scans and the 360° CBCT scans were viewed in separate pre-randomized orders in each session. All examination sessions were carried out in a quiet, darkened room. Prior to Sessions 1 and 2 the examiners were calibrated. The examiners were shown examples of CBCT images and radiographs of simulated resorption defects, of various sizes, created on teeth used in pilot studies. They were trained how to use the CBCT software and how to adjust the contrast of the digital periapical radiographs. Each investigator demonstrated an ability to assess the calibration images proficiently, prior to examining the experimental images.

The radiographs were viewed on a laptop computer (Dell Inspiron 1720; Dell, Round Rock, TX, USA) as a PowerPoint presentation (Microsoft, Seattle, WA, USA). A parallel radiograph and two parallax views were provided for each tooth under examination. The tooth to be examined was arrowed to avoid confusion. Examiners were asked to note down whether or not they thought there was an EIR lesion present on the root of the arrowed tooth. Confidence in their observation was recorded using a five point scale as follows: 1 – external resorption lesion definitely not present, 2 – probably not present, 3 – unsure, 4 – probably present and 5 – definitely present. The examiners were also asked to note, using the following 5 point scale, on which surface of the root the visualized lesion was located: 1 – mesially, 2 – distally, 3 – buccally, 4 – lingually and 5 – unsure. Finally, the examiners were asked to indicate the lesion they visualized, using the PowerPoints 'ink annotations' function located in 'pointer options'. The pointer created a red dot at a point on the slide of the examiners discretion. The examiner was asked to directly 'dot' any resorption lesion they could see on the arrowed tooth.

For the CBCT scans the examiners were presented with the primary reconstructed CBCT data. Prior to examining the scans, the examiner was tutored on how to upright the teeth on the scans using the One Volume Viewer software (J Morita). The examiner was then asked to scroll through the axial, coronal and sagittal slices for each tooth. Again, they were asked to note down whether or not a lesion was present, how confident they were about the presence or absence of the lesion, and on which root surface the lesion was located, using the same scales and methods as described for the radiograph examination. When the examiner identified a resorption lesion on the CBCT scan they were asked to notify the author and a static image, containing slices in all the orthogonal planes, which the examiner felt most clearly demonstrated the resorption, was copied to a PowerPoint presentation by the author. The examiner was then asked to mark the resorption lesion as before, in as many of the planes as s/he could, using the 'ink annotation' function. The dotted images were then saved.

Data analysis

The raw data were analysed using Stata™ software (Stata 10, College Station, TX, USA). The sample size of 10 teeth and the use of eight of examiners was predetermined by reference to previous work (Patel *et al.* 2009a). Power calculation using data from this study indicated that 10 teeth and 8 observers would be sufficient for a 90% chance of showing a difference of 0.2 in the receiver operator characteristic (ROC) area under the curve. The diagnostic accuracy of each imaging system and examiner in the detection of simulated EIR was assessed using receiver operating characteristic (ROC) curve analysis to estimate the area under the ROC curve (Az value). Sensitivity, specificity and positive and negative predicitive values (PPV) and (NPV) were determined. Kappa analysis was used to compare the repeatability of ROC scores for the three radiological techniques. A further Kappa analysis was carried out to compare the accuracy of the imaging techniques in allowing the examiners to identify the surface on which the resorption lesion was created.

Results

The ROC analysis revealed a lower Az value for digital periapical radiography (0.584) in the detection of small EIR lesions when compared with 180° (0.969) and 360° (0.979) CBCT ($P < 0.001$). The Az value for intraoral radiography in the detection of larger lesions was 0.733 and was less than that for 180° (1.000) and 360° (1.000) CBCT ($P < 0.001$). Regardless of the lesion size, the overall Az value for intraoral radiography was lower (0.665), compared to Az values for 180° (0.984) and 360° (0.990) CBCT ($P < 0.001$) (Table 1).

Regardless of lesion size the sensitivity of intraoral radiography was lower (86.9) compared to 180° (100) and 360° (100) CBCT ($P < 0.001$). The specificity of 180° and 360° CBCT was 92.3 and 95.5 respectively. These results were, again, regardless of lesion size and were better than the specificity of periapical radiography, which was 43.1 ($P < 0.001$). When comparing 'no lesion' with 'any lesion' the PPV for radiographs was 43.1 compared to values of 95.6 for 180° CBCT and 97.5 for 360° CBCT ($P < 0.001$). CBCT, regardless of the degree of rotation had NPV of 100 compared to NPVs of 85 for intraoral radiography ($P < 0.01$) (Table 2).

The kappa values for intra-examiner agreement were 0.292 for intraoral radiography, 0.853 for 180° CBCT and 0.895 for 360° CBCT ($P < 0.001$) (Table 3). The kappa scores for inter-examiner reproducibility were 0.122 for radiographs and 0.639 and 0.672 for 180° and 360° CBCT respectively ($P < 0.001$) (Table 4).

Table 1 Comparison of agreement with gold standard diagnosis [mean (SD) area under the curve from ROC analysis] for the three radiological techniques, $n = 8$

	Radiograph	180° CBCT	360° CBCT
No lesion vs. both sizes of lesion	0.665 (0.057)	0.984* (0.013)	0.990* (0.014)
No lesion vs. small lesion	0.584 (0.051)	0.969* (0.026)	0.979* (0.029)
No lesion vs. large lesion	0.733 (0.098)	1.000* (0.000)	1.000* (0.000)

*significantly different from radiographs ($P < 0.001$).

Table 2 Mean (SD) percentage sensitivity, specificity, PPV and NPV for each radiological technique comparing 'no lesion' with 'any lesion'

	Sensitivity	Specificity	PPV	NPV
Radiograph	86.9 (9.3)*	43.1 (4.6)*	43.1 (13.3)*	85 (12.0)†
180° CBCT	100 (0.0)	92.3 (5.5)	95.6 (3.2)	100 (0.0)
360° CBCT	100 (0.0)	95.5 (4.8)	97.5 (2.7)	100 (0.0)

*Significantly different from 180º and 360º CBCT ($P < 0.001$), †$P < 0.01$.

Table 3 Comparison of repeatability of ROC scores (mean (SD) Kappa values) for the three radiological techniques, $n = 8$

	Radiograph	180º CBCT	360º CBCT
Original vs repeated score	0.292 (0.148)	0.853* (0.151)	0.895* (0.065)

*Significantly different from radiographs ($P < 0.001$).

Table 4 Kappa values for inter-examiner agreement in reading radiographs and CBCT images

	Radiograph	180º CBCT	360º CBCT
Inter-examiner kappa score	0.122*	0.639	0.672

*Significantly different from 180º and 360º CBCT ($P < 0.001$).

Table 5 Comparison of accuracy in identifying the affected surface (mean (SD) kappa values) for the three radiological techniques, $n = 8$

	Radiograph	180º CBCT	360º CBCT
Gold standard vs surface score	0.248 (0.092)	0.946* (0.031)	0.964* (0.022)

*Significantly different from radiographs ($P < 0.001$).

Examiners were also significantly better able to identify the exact location of the resorption lesions with CBCT than they were with radiographs ($P < 0.001$) (Table 5). There was no significant difference in the ability of 180° and 360° CBCT to detect simulated EIR.

Discussion

In this study, simulated EIR cavities were created on mandibular incisor teeth in dry human mandibles. Under ideal circumstances human cadavers would have been used in order to accurately replicate the soft tissue attenuation and scatter from the X-ray source. Appropriate specimens, however, were not available for this study. The X-ray beam for the intraoral radiographs and CBCT scans were attenuated by placing a 1 cm thick acrylic plate (Evonik), as used by Noujeim *et al.* (2009), between the X-ray source and the specimen. It may be argued that a thickness of acrylic greater than 1 cm would be necessary to reproduce the absorbtion and scatter created during clinical CBCT imaging as the X-ray beam encounters the cervical spine and other areas of the mandible. A pilot study demonstrated that the images captured using the 1 cm thick acrylic as a soft tissue equivalent closely mimicked corresponding clinical images on patients. However, this is a subjective assessment.

The intraoral radiographs were captured using a digital system. This produced a dynamic image allowing the user to alter brightness and contrast easily. Borg *et al.* (1998) have shown that there is no difference between digital [PSP and charged couple device (CCD)] and film-based radiographs in the detection of artificially simulated external resorption lesions. Another study, however, reported that conventional film and CCD sensors were better at detecting external resorption than PSP sensors (Kamburoğlu *et al.* 2008). The authors conceded that the reason for the difference may have been due to limitations of the specific PSP system used by them in their study (Orex Digident, Yokneam, Israel). The PSP system used in this study, on the other hand, was the latest generation of the one used by Borg *et al.* (1998).

The periapical radiographs were viewed as PowerPoint slides. Theoretically transferring digital images to PowerPoint may affect the diagnostic yield of the radiographs, but with care is unlikely. Steps were taken during the original process of saving the images to minimize any reduction in image quality during the preparation of the slides. On close inspection, no subjective difference in image quality was noticed between the original images and the same images viewed as PowerPoint slides.

A final CBCT data set is based on a series of combined individual basis images. Increasing the degree of rotation of the CBCT scanners' X-ray source and detector means an increased number of basis images (and the acquisition of more data), with a potential improvement in diagnostic yield. However, with higher degrees of rotation comes increased radiation exposure to the patient. Two sets of CBCT scans were taken in this study, differing only in the degree of rotation of the X-ray source around the experimental specimen – either 180° or 360°. This allowed us to assess any difference in diagnostic yield resulting from the increased radiation associated with the higher degree of rotation. The placement of the specimens in specially created jigs during imaging ensured that all images were standardized and reproducible.

It would have been desirable to use maxillary anterior teeth in this experiment. These are the teeth most frequently subject to luxation (Andreasen & Vestergaard Pedersen 1985) and exarticulation injuries (Andreasen *et al.* 1995a,b,c,d). However, intact human maxillae with sufficient and appropriate teeth to carry out the experiment proved impossible to source. Consequently, the resorption was simulated on incisors in human mandibles. After maxillary incisors these are the teeth most commonly subject to dental traumatic injuries (Lenstrup & Skieller 1959, Andreasen & Hjørting-Hansen 1966a, Andreasen & Vestergaard Pedersen 1985). The simulated EIR lesions were machined in the roots using steel rose head burs. Every effort was made to ensure standardization and reproducibility of the cavity sizes, using similar techniques to other authors (Andreasen *et al.* 1987, Hintze *et al.* 1992). The simulated external inflammatory root resorption lesions created in this study were hemispherical. This clearly does not reflect the clinical reality in which root resorption lesions are irregular in shape. Future studies involving the use of standardized simulated resorption lesions of irregular shape are necessary. As stated previously, EIR lesions are associated with destruction of the adjacent bone, represented radiographically as radiolucencies. Under ideal circumstances this boney destruction would have been replicated in the experiment. However, in order to create access to prepare the boney defects accurately at a point directly adjacent to the simulated resorption defects, the intact mandibles would have to be split in a coronal plane through their sockets. The different segments would then have to be repositioned prior to imaging. This would be highly destructive of valuable human samples, and would inevitably produce radiographic representations of the fracture lines on the images to be examined. Examination of the root surfaces would most likely be impaired by this process and so it was decided not recreate these boney defects.

The results of this study are in agreement with earlier studies which indicate that intraoral radiography is an inadequate method for detecting resorption defects at an early stage (Andreasen *et al.* 1987, Chapnick 1989, Goldberg *et al.* 1998). Two cavity sizes were used in this experiment – small (0.5 mm diameter and 0.25 mm depth) and large (1 mm diameter and 0.5 mm depth). The dimensions of these cavities were similar to the 'small' and 'medium' cavity dimensions, respectively, used in previous studies (Andreasen *et al.* 1987, Chapnik *et al.* 1989, Goldberg *et al.* 1998). In the study by Andreasen *et al.* (1987) no small resorption defects could be detected using film based intraoral radiographs despite the fact that the pre-operative radiograph and multiple angled radiographs of the subject teeth were available to the examiners. In a similar study by Goldberg *et al.* (1998) examiners also failed to diagnose any small resorption defects using conventional radiography when the pre-operative radiographs were not available to them for comparison purposes. In an attempt to overcome the shortcomings of conventional radiography, the ability of other imaging systems to detect external root resorption have been investigated. Digital subtraction radiology (Kravitz *et al.* 1990, Hintze *et al.* 1992) and tune apertured computed tomography (Nance *et al.* 2000) have been shown to be better capable of identifying simulated external root resorption cavities than conventional intraoral radiography. In addition, flat panel volume computerized tomography has potential applications in the detection of external root resorption at an early stage (Hahn *et al.* 2009).

Case reports in the literature outlining the usefulness of CBCT and CT as diagnostic and treatment planning tools in the diagnosis and management of external resorption have been restricted to cases of external cervical resorption (Kim *et al.* 2003, Cohenca *et al.* 2007, Patel & Dawood 2007). Clinical studies directly comparing the ability of intraoral radiographs and CBCT to detect and diagnose EIR are limited. However, one clinical study did report that CBCT is superior to conventional radiography in diagnosing and determining the extension of non-specific inflammatory resorption on root surfaces (Estrela *et al.* 2009). Patel *et al.* (2009b), in a further clinical study, compared the accuracy of conventional intraoral radiography and CBCT in the diagnosis and management of external cervical and internal resorption lesions. The authors reported CBCT to be 100% accurate in the diagnosis of the presence and type of the root resorption and the overall sensitivity of intraoral radiographs was lower than CBCT. Critically, however, the nature of these clinical studies does not preclude the occurrence of false negative results. That is, as the root surfaces cannot be visually examined, it is impossible to rule out the presence of resorption lesions which may not have been detected by the imaging systems. For this reason, *ex vivo* studies similar to the current one are necessary to accurately measure and compare the sensitivity of imaging devices in the detection of EIR.

One *ex vivo* study (Alqerban *et al.* 2009) compared the ability of two CBCT systems and conventional panoramic radiography to detect simulated external surface resorption lesions, of varying sizes, associated with canine impaction. The authors reported that small and medium field of view CBCT systems were superior to conventional panoramic radiography in the detection of simulated external resorption cavities, regardless of the cavity size. There was no statistical difference between the diagnostic ability of the CBCT systems. However, conventional panoramic radiography is rarely utilized in endodontic specific investigations. Intraoral radiography is currently the imaging technique of choice when assessing traumatically injured permanent teeth which may develop EIR (Flores *et al.* 2007a,b). The current study directly compares the ability of CBCT and digital periapical radiography to detect early EIR lesions under experimental conditions. In that regard, to our knowledge, this study is unique. The selection of teeth with pre-experimental intact surfaces ensured that the experimental resorption cavities were the only ones on the root surfaces.

In this study some small lesions were identified on periapical radiographs. The radiographs had a poor Az value of 0.584 for the detection of small cavities in the ROC analysis. This contrasts starkly with the Az values approaching 1.000 for CBCT. The specificity of periapical radiography was poor. Part of the reason for this may have been due to the possible 'expectation' of some examiners that they should visualize simulated resorption defects as they were aware that this is what they were looking for. A contributory factor may also have been the difference in the patterns of boney trabeculae between mandibles. In one mandible in particular the superimposition of boney trabeculae on the roots of some teeth seemed to mimic the experimental defects. In a clinical setting the examiners may have been more confident that what they were viewing was a normal trabecular pattern as they would not necessarily have been expecting to see resorptive defects. Nevertheless the same 'expectations' would have applied when the examiners viewed the CBCT images. The results clearly demonstrate that CBCT has excellent sensitivity and specificity in the detection of simulated external resorption lesions, and that CBCT performs significantly better than digital intraoral radiography in this regard. This is due to the fact that CBCT provides information in the third dimension, coupled with the fact that images can be reconstructed such that overlying noise is eliminated.

The intra-examiner agreement for periapical radiographs in this study was poor. This suggests that intraoral periapical radiography is an unreliable method of detecting simulated early EIR. It is likely that the anatomical noise and the compression of three-dimensional anatomical structures associated with the periapical radiographs played a significant part. The noise created by the trabecular patterns was, again, likely to have confused examiners leading to uncertainty when attempting to detect simulated resorption defects. The intra-examiner kappa scores for CBCT, however, were very good and undoubtedly were due to the fact that this imaging technique overcomes many of the shortcomings of conventional radiographic imaging.

The inter-examiner agreement was significantly better with CBCT compared to digital radiography. When taken together the inter and intra examiner kappa scores obtained here provide evidence of the validity and reliability of CBCT for detecting EIR defects. The reliability and validity of intraoral radiography is poor, in comparison.

The effective radiation dose to patients when using CBCT is higher than digital radiography and any benefit to the patient of the CBCT scan should outweigh any potential risks of the procedure in order to be justified (Farman & Farman 2005). The radiation should be as low as reasonably achievable (ALARA). This study does demonstrate that when all other exposure parameters are the same, limited volume CBCT scans with 360° of rotation are no better at detecting EIR than the same scans taken with 180° of rotation, and as such cannot be justified in a clinical setting.

Given the financial and emotional impact that premature tooth loss can have on individuals and given the evidence presented here and in other similar literature, a re-thinking on how traumatized teeth are radiographically assessed and followed up is warranted. Nevertheless, radiological imaging is only one of a number of diagnostic aids used in dentistry. In clinical situations in which a definitive decision can be made about the pulpal status of a tooth based on sensibility testing, clinical signs and symptoms and conventional radiographic imaging, endodontic treatment will be indicated without the need for further CBCT imaging. Regardless of the type of ERR, CBCT imaging can only be justified clinically in situations where the possible information it provides will impact directly on treatment.

Conclusion

The results of this study highlight the limitations of intraoral periapical radiography in the detection of simulated EIR. CBCT overcomes these shortcomings and provides a reliable and valid method of detecting artificially created EIR defects. Earlier detection of the resorption process in 'at risk' individuals may lead to more prompt and appropriate treatment, ultimately resulting in improved prognoses for affected teeth.

References

Alqerban A, Jacobs R, Souza PC, Willems G (2009) *In-vitro* comparison of 2 cone-beam computed tomography systems and panoramic imaging for detecting simulated canine impaction-induced external root resorption in maxillary lateral incisors. *American Journal of Orthodontics and Dentofacial Orthopedics* **136**, 764e1–e11.

Andreasen JO (1981) Relationship between surface and inflammatory root resorption and changes in the pulp after replantation of permanent incisors in monkeys. *Journal of Endodontics* **7**, 294–301.

Andreasen JO, Andreasen FM (2007) Avulsions. In: Andreasen JO, Andreasen FM, Andersson L, eds. *Textbook and Colour Atlas of Traumatic Injuries to the Teeth*, 4th edn. Chapter 17. Oxford: Blackwell Munksgaard, pp. 444–88.

Andreasen JO, Hjørting-Hansen E (1966a) Replantation of teeth. I. Radiographic and clinical study of 110 human teeth replanted after accidental loss. *Acta Odontoligica Scandinavica* **24**, 263–86.

Andreasen JO, Hjørting-Hansen E (1966b) Replantation of teeth. II. Histological study of 22 replanted anterior teeth in humans. *Acta Odontoligica Scandinavica* **24**, 287–306.

Andreasen FM, Vestergaard Pedersen B (1985) Prognosis of luxated permanent teeth – the development of pulp necrosis. *Endodontics and Dental Traumatology* **1**, 207–20.

Andreasen FM, Sewerin I, Mandel U, Andreasen JO (1987) Radiographic assessment of simulated root resorption cavities. *Endodontics and Dental Traumatology* **3**, 21–7.

Andreasen JO, Borum MK, Jacobsen HL, Andreasen FM (1995a) Replantation of 400 avulsed permanent incisors. 4. Factors related to periodontal ligament healing. *Endodontics and Dental Traumatology* **11**, 76–89.

Andreasen JO, Borum MK, Jacobsen HL, Andreasen FM (1995b) Replantation of 400 avulsed permanent incisors. 1. Diagnosis of healing complications. *Endodontics and Dental Traumatology* **11**, 51–8.

Andreasen JO, Borum MK, Jacobsen HL, Andreasen FM (1995c) Replantation of 400 avulsed permanent incisors. 2. Factors related to pulpal healing. *Endodontics and Dental Traumatology* **11**, 59–68.

Andreasen JO, Borum MK, Andreasen FM (1995d) Replantation of 400 avulsed permanent incisors. 3. Factors related to root growth. *Endodontics and Dental Traumatology* **11**, 69–75.

Bender IB, Seltzer S (1961) Roentgenographic and direct observation of experimental lesions in bone: I. *Journal of the American Dental Association* **62**, 152–60.

Borg E, Källqvist A, Gröndahl K, Gröndahl H-G (1998) Film and digital radiography for detection of simulated root resorption cavities. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiolology and Endododontology* **86**, 110–4.

Chapnick L (1989) External root resorption: an experimental radiographic evaluation. *Oral Surgery Oral Medicine Oral Pathololog*y **67**, 578–82.

Cohenca N, Simon JH, Mathur A, Malfaz JM (2007) Clinical indications for digital imaging in dento-alveolar trauma. Part 2: root resorption. *Dental Traumatology* **23**, 105–13.

Cvek M (1973) Treatment of non-vital permanent incisors with calcium hydroxide. II. Effect on external root resorption in luxated teeth compared with effect of root filling with gutta percha. *Odontologisk Revy* **24**, 343–54.

Cvek M (1992) Prognosis of luxated non-vital maxillary incisors treated with calcium hydroxide and filled with gutta percha. *Endodontics and Dental Traumatology* **8**, 45–55.

Cvek M (2007) Endodontic management and the use of calcium hydroxide in traumatized permanent teeth. In: Andreasen JO, Andreasen FM, Andersson L, eds. *Textbook and Colour Atlas of Traumatic Injuries to the Teeth*, 4th edn. Chapter 22. Oxford: Blackwell Munksgaard, pp. 598–657.

Dumsha T, Hovland EJ (1995) Evaluation of long-term calcium hydroxide treatment in avulsed teeth – an *in vivo* study. *International Endodontic Journal* **28**, 7–11.

Estrela C, Reis Bueno M, Alencar AHG *et al.* (2009) Method to evaluate inflammatory root resorption by using cone beam computed tomography. *Journal of Endodontics* **35**, 1491–7.

Farman AG, Farman TT (2005) A comparison of 18 different X-ray detectors currently used in dentistry. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **99**, 485–9.

Flores MT, Andersson L, Andreasen JO *et al.* (2007a) Guidelines for the management of traumatic dental injuries. I. Fractures and luxations of permanent teeth. *Dental Traumatology* **23**, 66–71.

Flores MT, Andersson L, Andreasen JO *et al.* (2007b) Guidelines for the management of traumatic dental injuries. I. Avulsion of permanent teeth. *Dental Traumatology* **23**, 130–6.

Goldberg F, De Silvio A, Dreyer C (1998) Radiographic assessment of simulated external root resorption cavities in maxillary incisors. *Endodontics and Dental Traumatology* **14**, 133–6.

Gröndahl H-G, Huumonen S (2004) Radiographic manifestations of periapical inflammatory lesions. *Endodontic Topics* **8**, 55–67.

Hahn W, Fricke-Zech S, Fricke J *et al.* (2009) Detection and size differentiation of simulated tooth root defects using flat-panel volume computerized tomography (fpVCT). *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **107**, 272–8.

Hammarström L, Lindskog S (1985) General morphological aspects of resorption of teeth and alveolar bone. *International Endodontic Journal* **18**, 93–108.

Hintze H, Wenzel A, Andreasen FM, Sewerin I (1992) Digital subtraction radiography for assessment of simulated root resorption cavities. Performance of conventional and reverse contrast modes. *Endodontics and Dental Traumatology* **8**, 149–54.

Kamburoğlu K, Tsesis I, Kfir A, Kaffe I (2008) Diagnosis of artificially induced external root resorption using conventional intraoral film radiography, CCD, and PSP: an *ex vivo* study. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology & Endodontology* **106**, 885–91.

Kim E, Kim K-D, Roh B-D, Cho Y-S, Lee S-J (2003) Computed tomography as a diagnostic aid for extracanal invasive resorption. *Journal of Endodontics* **29**, 463–5.

Kravitz LH, Tyndall DA, Bagnell CP, Dove SB (1990) Assessment of external root resorption using digital subtraction radiography. *Journal of Endodontics* **18**, 275–84.

Kundel HL, Revesz G (1976) Lesion conspicuity, structured noise, and film reader error. *American Journal of Roentgenology* **126**, 1233–8.

Lenstrup K, Skieller V (1959) A follow up study of teeth replanted after accidental loss. *Acta Odontologica Scandinavia* **17**, 503–9.

Liedke GS, Silveira HED, Silveira HLD, Dutra V, Figueiredo JAP (2009) Influence of voxel size in the diagnostic ability of cone beam tomography to evaluate simulated external root resorption. *Journal of Endodontics* **35**, 233–5.

Nance RS, Tyndall D, Levin LG, Trope M (2000) Diagnosis of external root resorption using TACT (tuned-aperture computed tomography). *Endodontics and Dental Traumatology* **16**, 24–8.

Noujeim M, Prihoda TJ, Langlais R, Nummikoski P (2009) Evaluation of high-resolution cone beam computed tomography in the detection of simulated interradicular bone lesions. *Dentomaxillofacial Radiology* **38**, 156–62.

Patel S, Dawood A (2007) The use of cone beam computed tomography in the management of external cervical resorption lesions. *International Endodontic Journal* **40**, 730–7.

Patel S, Dawood A, Mannocci F, Wilson R, Pitt Ford T (2009a) Detection of periapical bone defects in human jaws using cone beam computed tomography and intraoral radiography. *International Endodontic Journal* **42**, 507–15.

Patel S, Dawood A, Wilson R, Horner K, Mannocci F (2009b) The detection and management of root resorption lesions using intraoral radiography and cone beam computed tomography – an *in vivo* investigation. *International Endodontic Journal* **42**, 831–8.

Revesz G, Kundel HL, Graber MA (1974) The influence of structured noise on the detection of radiologic abnormalities. *Investigative Radiology* **6**, 479–86.

Silveira HL, Silveira HE, Liedke GS, Lermen CA, Santos RB, Figueiredo JAP (2007) Diagnostic ability of computed tomography to evaluate external root resorption *in vitro*. *Dentomaxillofacial Radiology* **36**, 393–6.

Tronstad L (1988) Root resorption – etiology, terminology and clinical manifestations. *Endodontics and Dental Traumatology* **4**, 241–52.

Trope M (2002) Root resorption due to dental trauma. *Endodontic Topics* **1**, 79–100.

Webber RL, Messura JK (1999) An in vivo comparison of diagnostic information obtained from tuned-aperture computed tomography and conventional dental radiographic imaging modalities. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **88**, 239–47.