



CASE REPORT

Three-dimensional, non-destructive visualization of vertical root fractures using flat panel volume detector computer tomography: an *ex vivo* in vitro case report

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Abstract

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Aim To detect and to visualize radiographically vertical root fractures in extracted teeth with a prototype of a novel, high resolution, three-dimensional flat panel volume detector computer tomograph (FD-VCT) system.

Summary Five teeth with root fillings and clinical symptoms such as fistulas and isolated periodontal pockets of 8 mm or more were extracted after dental radiography indicating lateral or periapical lesions. Vertical root fractures or cracks were suspected because of the symptoms and clinical findings were evident after extraction in all cases but fracture lines were not visible on routine dental radiographs acquired before extraction. The extracted teeth were explored with a prototype of a FD-VCT. Using the FD-VCT, in all cases vertical root fractures or crack lines could be detected clearly in different views, depiction-modes and cross-sections at a spatial resolution of 140 μm . The evaluation of the fracture lines and teeth could be performed in three-dimensional views. The FD-VCT findings were confirmed by detailed inspection of the extracted teeth.

Key learning points

- The FD-VCT is an innovative diagnostic tool for non-destructive, three-dimensional evaluation of extracted teeth in pre-clinical and experimental studies.
- The FD-VCT allows precise visualization and evaluation of vertical root fractures or cracks in extracted teeth.
- Clinical application of the system may be possible if technical modifications reduce the exposure dose: the high resolution detector systems of the FD-VCT should be combined with radiation systems that focus the radiation to the area of interest.

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Introduction

Vertical root fractures are longitudinally oriented fractures of roots initiated in the crown or at the root, respectively. Clinical diagnosis of this type of fracture or crack is difficult as the symptoms are nonspecific and resemble post-treatment disease following root canal treatments or periodontal disease (Tamse 1988). The vertical root fracture may be accompanied by pain of various kinds, swelling, mobility, isolated periodontal pockets exposing a probing depth of 8 mm or more and sometimes fistulous tracts (Meister *et al.* 1980, Tamse 1988, Testori *et al.* 1993, Tamse *et al.* 1999, Fuss *et al.* 1999). Conventional diagnostic methods may indicate vertical root fractures or cracks indirectly but they do not allow visualization of the fracture line itself. Furthermore, interpretation of these clinical signs is difficult and often doubtful (Tamse *et al.* 1999).

A presumed vertical root fracture cannot be verified and visualized in conventional dental radiographs except in very distinct cases (Rud & Omnell 1970, Pitts & Natkin 1983). Radiographic observations such as periapical or lateral radiolucencies are unspecific. Vertical root fracture inevitably leads to the extraction of the affected tooth, therefore, clear diagnosis is desirable.

The inability of conventional imaging techniques to visualize vertical root fractures precisely in a non-destructive approach, emphasizes the importance of developing alternative imaging modalities facilitating analysis of vertical root fractures (Nair *et al.* 2001). In this context, it is noteworthy that new imaging systems such as cone beam computed tomography (CT) or digital volume tomography have been introduced in dentomaxillo-facial imaging in implantology and oral surgery (Siewerdsen & Jaffray 1999, Fortin *et al.* 2002, Fuhrmann *et al.* 2003). From the theoretical point of view, such systems allow detection of vertical root fractures. However, the resolution of conventional CT used in medicine for clinical diagnostics is not sufficient for detection of root fractures in all cases (Youssefzadeh *et al.* 1999).

In contrast to conventional CT-systems, the prototype of a flat panel volume detector CT (FD-VCT) offers the opportunity to explore complete arches or heads at a high resolution of 140 μm . The FD-VCT allows superior three-dimensional resolution when compared with conventional CT-systems (Ning *et al.* 2000, 2003, Kiessling *et al.* 2004, Heidrich *et al.* 2005). The system is based on new detector technology and has been adopted in several experimental approaches for three-dimensional evaluation of very small structures such as noninvasive, high-resolution monitoring of tumour angiogenesis (Ning *et al.* 2000, 2003, Kiessling *et al.* 2004).

In a pre-clinical pilot study, suitability of FD-VCT for visualization of teeth and root canal systems has already been proven (Heidrich *et al.* 2005). Even lateral canals, communications of root canals and denticles can be visualized three-dimensionally with this nondestructive approach. The present study, investigated whether vertical root fractures could be detected and visualized with this new tomographic technology.

Materials and methods

Subjects

Five patients with root filled teeth that were to be extracted because of pain, periodontal pockets and sinus tracts were included. The symptomatic teeth were extracted because of these clinical signs indicating vertical root fractures or cracks.

Dental X-ray and photography

Conventional dental radiographs were acquired from all five teeth for the purpose of diagnosis before extraction and evaluated by two experienced dentists. Additionally, conventional images were acquired from all teeth immediately after extraction and before evaluation with FD-VCT.

Flat panel volume detector CT

Three-dimensional analysis of the extracted teeth was performed with a prototype of a flat panel volume detector CT (General Electric Global Research Centers, Niskayuna, NY, USA). The system allows three-dimensional, high resolution volumetry (Fig. 1). The gantry contains an X-ray tube (Performix 630; GE Medical Systems, New York, NY, USA) and two flat panel detectors. They perform a coupled rotation around a closed centre of rotation. The X-ray tube has a focus of 0.7 mm at a maximal voltage of 140 kV and a current of up to 400 mA. The power is limited to 20 kW. The CT dose index for a 16 cm standard phantom amounts to $0.172 \text{ mGy mA}^{-1}$, which is in the same level compared with commercially available MSCT-systems. Because of the lack of variable collimation of the X-ray in the prototype system, there is presently no permission for clinical use.

Both flat panel detectors are $20.5 \times 20.5 \text{ cm}$. They are arranged at an angle of 120° parallel to the main axis of the system. Both detectors contain a diode-array made of amorphous silicon (a-Si) covered by a layer of thallium doped caesium-iodide for purpose of X-ray absorption. The sensor array is composed of 1024×1024 single elements. The FD-VCT is run as an axial system, all 1024 columns are read out parallel to the main axis of the system. The high density of detector elements allows evaluation of objects at a high isotropic spatial resolution. The pixel-size amounts to $200 \times 200 \mu\text{m}$. Because of the



Figure 1 Prototype of the flat panel volume detector computer tomograph system, University of Göttingen, Germany.

radiographic enlargement of 1.43, the spatial resolution amounts to 140 μm ; 3.6 line-pairs are read out per mm at a high cone-head speed. One scan is performed in about 7 s.

Furthermore, the FD-VCT contains a network of different hard and software components. A central computer controls a stator and a rotor computer. Thereby, the stator computer operates the gantry, the rotor computer pilots the X-ray tube and the detectors. In addition, there are several computers for image-construction and archival storage of data. There is also a work-station with special software for evaluation of the data-sets (Volume viewer, Vox volume 3.0.64).

After acquiring data, image reconstruction was performed. The sum of the data-records resulted in five complete volume data sets. This allowed three-dimensional reconstruction of the teeth from all directions. Further editing of the data records was conducted at an Advantage Windows Workstation. Adequate colours, opacity, and contrasts were defined for the teeth. This led to two algorithms for evaluation of teeth. The transparency mode provides a view through the teeth and an overview of the root canal system. The other algorithm is a special tooth algorithm for distinct differentiation of enamel, dentine, and root canals or fillings, respectively (Heidrich *et al.* 2005). The system allows evaluation of the images with different colours to emphasize certain structures.

Results

Five cases were included in this *ex vivo* study. Clinical inspection after extraction of the radiographically well filled teeth yielded root fractures or cracks in all cases (Figs 2b, 3b, 4b, 5b and 6b). Sometimes the cracks were of microscopic size (Figs 2b, 3b and 4b).

In none of the depicted cases was the fracture line detectable on conventional radiographs (Figs 2a, 3a, 4a, 5a and 6a). Separation of the fragments was not observed in any case radiographically. However, in all cases periapical and lateral lesions were detected radiographically, accompanied by clinical signs such as fistulous tracts and isolated periodontal pockets. In one example, the fistulous tract was marked with a gutta-percha point (Fig 5a). These findings indicated the presence of a vertical root fracture or crack indirectly in all cases. Hence, surgery was not considered a viable treatment alternative.

The evaluation of the extracted teeth with the FD-VCT yielded fractures and cracks in all cases. In this context, it has to be borne in mind that specific images are only screen shots

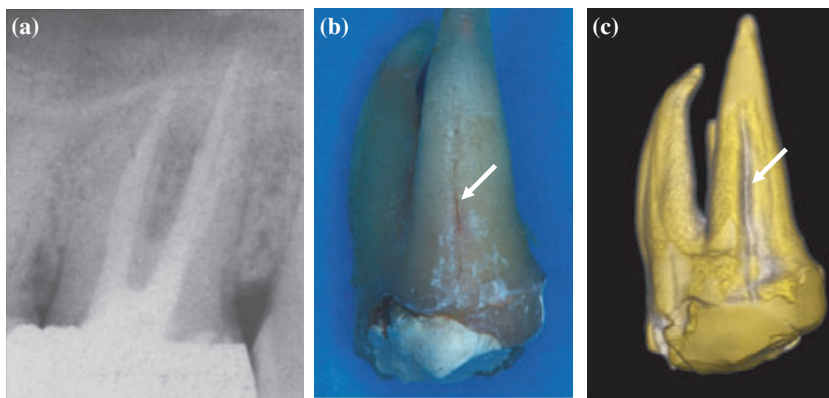


Figure 2 Tooth A: maxillary second molar with vertical hairline crack of the palatal root. The tooth had a fistula on the palatal aspect and a periodontal pocket at the site of the fracture. There was a crack on the palatal root (b) which was illustrated well with flat panel volume detector computer tomograph (c, arrows). No radiographic sign indicated the fracture line before extraction (a).

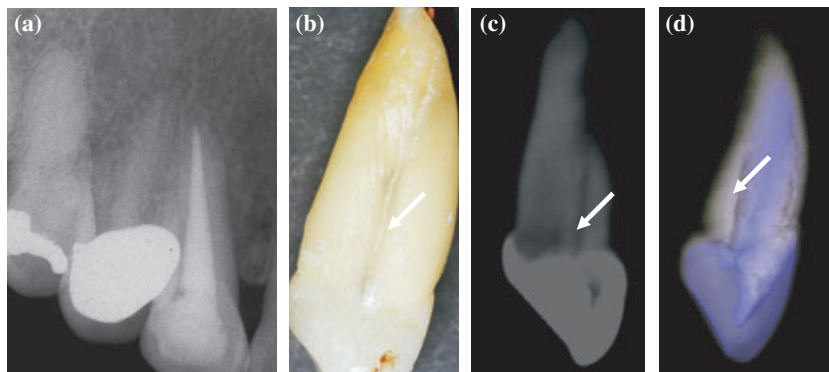


Figure 3 Tooth B: upper canine with vertical crack of the root. The hairline-crack, visible clinically after extraction (b) can be detected in longitudinal section (c) and external overview (d) using the flat panel volume detector computer tomograph (arrows). The crack was not visible in the conventional dental X-ray (a).

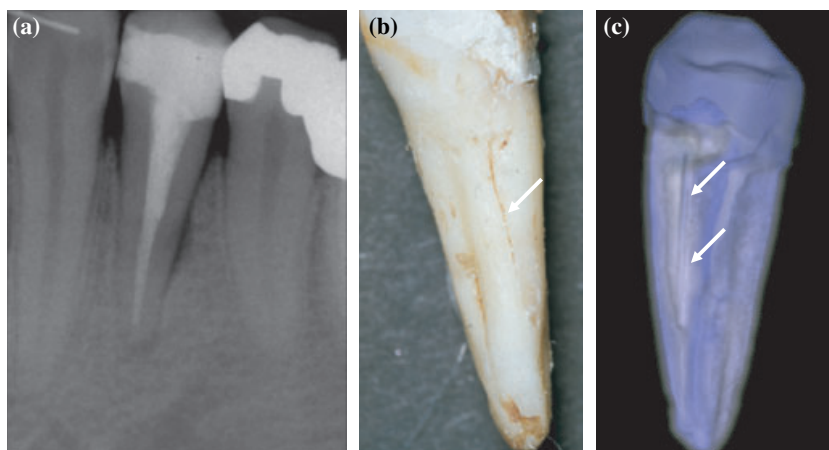


Figure 4 Tooth C: first mandibular premolar. The hairline-crack, visible clinically after extraction (b) can be detected with the flat panel volume detector computer tomograph (c, arrows). Periapical and lateral radiolucent area of bone loss give a clear hint on a vertical root fracture despite the fact that the fracture-line itself is not visible radiographically (a).

in different modes of the FD-VCT. During evaluation of the data in the computer, three-dimensional movements of the teeth and cross-sections in every level are possible, facilitating detection and exploration of the hairline cracks and other tooth structures. Examples are given in Figs 2–6.

In horizontal and vertical cross-sections (Figs 3c, 5f,g and 6d,e), fracture lines were shown clearly despite the artefacts induced by the gutta-percha (Fig. 6e). Using the tooth-algorithms developed especially for evaluation of dental hard tissues, the fracture lines were also detectable in a three-dimensional overview of the whole tooth (Figs 2c, 3d, 4c, 5c–e and 6c). Cracks may appear a little bit wider on FD-VCT images because of the semi-transparency of the FD-VCT images.

Discussion

This *ex vivo* pilot study, aimed to evaluate visualization of vertical root fractures with a new flat panel volume detector CT system compared with clinically acquired radiographs.

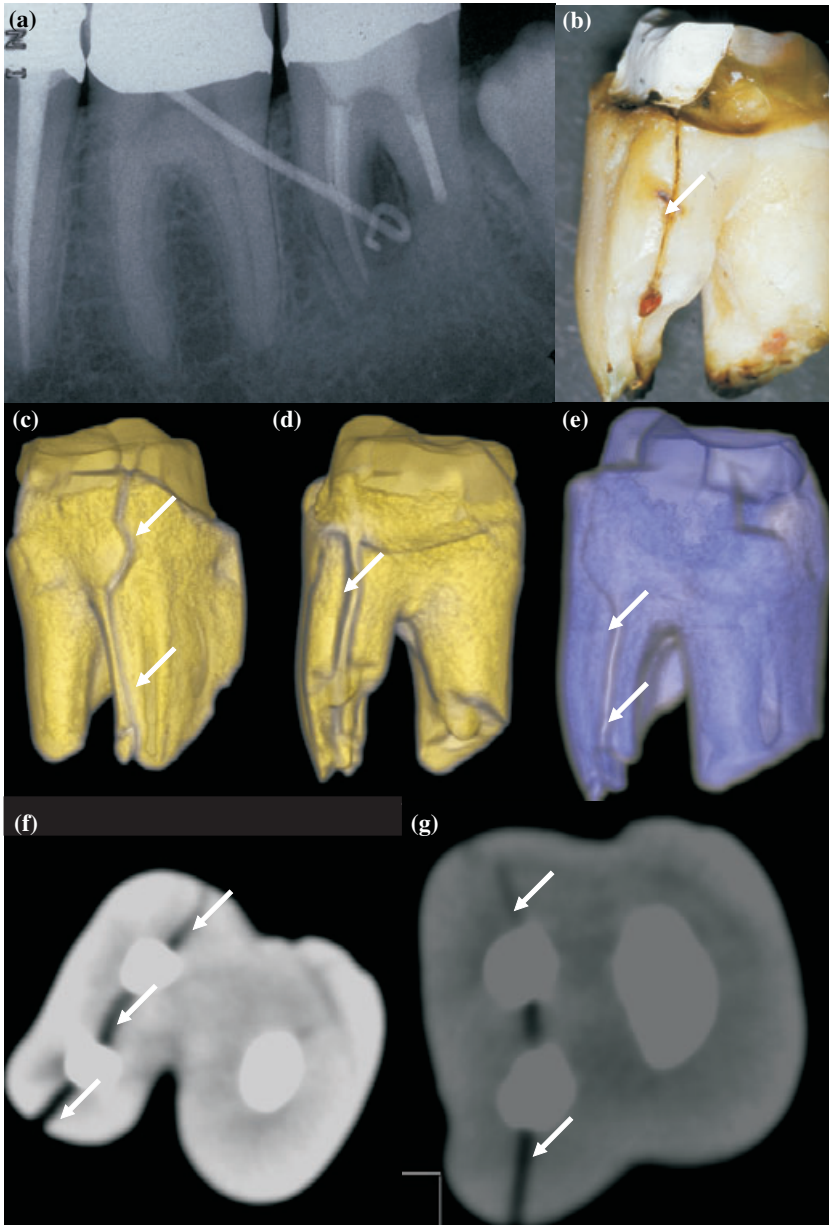


Figure 5 Tooth D: second mandibular molar with previous apicectomy. The extracted tooth shows a fracture of the mesial root (b). Vertical fracture lines are demonstrated clearly by different cross sections (f, g), views and modes (c, d, e) in flat panel volume detector computer tomograph (arrows). Different colours were used (c, d, e) in the special tooth-algorithm for visualization of the fracture line. Dental X-ray (a): furcational radiolucency and a gutta-percha point inside the sinus tract, the fracture line on the mesial root is not evident.

In none of the cases the fracture lines were detectable on conventional radiographs although vertical root fractures or cracks had been expected in all cases because of the clinical symptoms and signs. The photographs of the freshly extracted and cleaned teeth revealed root fractures in all cases, sometimes of microscopically small size. In all cases, the root fractures were detectable three-dimensionally and could be visualized precisely with FD-VCT. Because of its high linearity and high isotropic resolution, FD-VCT is able to

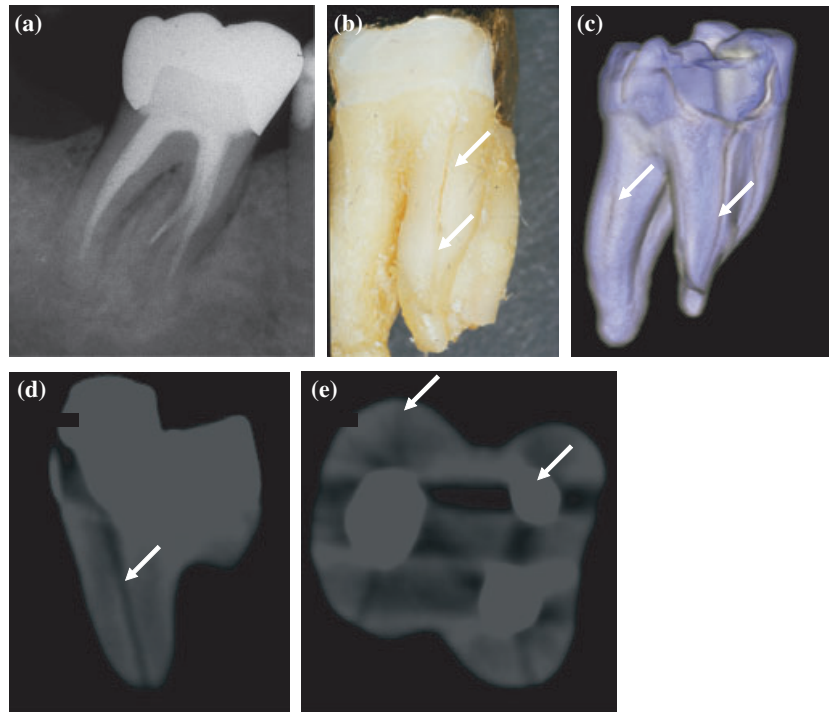


Figure 6 Tooth E: First mandibular molar. (b) Vertical cracks in mesial and distal root. Fracture lines are evident in different cross-sections (d, e), modes (c, d, e) and projections performed with flat panel volume detector computer tomograph (arrows), but not in dental X-ray (a).

depict microscopically small structures such as incomplete root fractures. In a previous pilot study, with FD-VCT, very small root canals and lateral canals had already been visualized successfully (Heidrich *et al.* 2005). The quality of the images is not hampered by the gutta-percha root filling material. With FD-VCT, even the influence of metallic restorations such as crowns or amalgam fillings on image quality is not substantial as one would expect following experiences gained in conventional CT. No beam hardening-artefacts were observed in a pilot study (Heidrich *et al.* 2005). Furthermore, because of the high resolution with isotropic voxels, there are also no partial-volume-effects (Heidrich *et al.* 2005).

The present study involved only a few cases that are not representative, but they were typical of cracked teeth. It is common for fracture lines not to be visible on a dental radiograph despite the fact that the clinical signs clearly indicate a vertical root fracture (Meister *et al.* 1980, Testori *et al.* 1993, Tamse *et al.* 1999).

Besides FD-VCT other imaging systems should be considered for nondestructive visualization of vertical root fractures. The micro-CT system with a high cubic resolution of 34 μm also allows investigation of microscopic alterations of tooth structures. These are pre-requisites for visualization of vertical root fractures, but only smaller objects can be explored because of the restricted small size of the gantry (Peters *et al.* 2000).

Conventional CT systems in medicine have a resolution of 500 μm . Their value in the detection of more pronounced vertical root fractures characterized by separation of the adjacent root segments has already been proven (Youssefzadeh *et al.* 1999). Nevertheless, detection of microscopically small hairline cracks was impossible. In that study, there were about one third false negative results, which may be attributed to the low resolution (Youssefzadeh *et al.* 1999). The fracture lines of tooth D evaluated in the present study

would be visible using conventional CT (Youssefzadeh *et al.* 1999), but hairline cracks of the other teeth will not because of the lack of resolution.

Another approach to imaging cracks in teeth would be the use of local-CT technology. Local-CT is a variant of CT that aims to reduce the radiation dose to the patient by using a narrow X-ray beam that only covers the area of interest in a varying number of projections. The primary parameter of the image quality is the number of projections, the resolution amounts to 220–324 μm which is lower than FD-VCT (van Daatselaar *et al.* 2004 a, b). Accordingly, the image quality is not as good as with FD-VCT.

The new Accuitomo system (Morita, Tokyo, Japan) is based on a cone beam X-ray CT. It allows radiographic evaluation of a localized cylindrical area of the head. The radiation dose is similar to a conventional panoramic film. The system is permitted for clinical use and the resolution is described by the manufacturer to be greater than two line pairs per mm. The nominal resolution amounts to 125 μm which is comparable to FD-VCT. It may be speculated that because of this high resolution, vertical root fractures may be detectable in clinical cases. However, there are no publications on this topic in the literature.

Further studies on detection of vertical root fractures have been performed with tuned aperture computer tomography (TACT). In this technique, several radiographic images are acquired using a special digital receptor. For acquisition of the different images, an X-ray source is moved in order to achieve projections at different angles. Data are reworked with a computer based on the summation of images for three-dimensional reconstruction of the teeth (Nair *et al.* 2001, 2003). Nevertheless, images are of inferior quality compared with the FD-VCT (Nair *et al.* 2003) and the sensitivity of TACT is not very high (55%) (Nair *et al.* 2001). However, an advantage of TACT is the low radiation exposure dose compared with any other conventional CT-systems (Nair *et al.* 2001, 2003).

An alternative, nonradiographic approach for nondestructive three-dimensional visualization of the root canal system may be nuclear magnetic resonance based imaging techniques (Kuhn 1990, Lockhart *et al.* 1992). This is especially true for magnetic resonance microscopy with a resolution of $100 \times 10 \times 10 \mu\text{m}^3$ or stray field imaging (Baumann *et al.* 1993). FD-VCT has a higher resolution than all other radiographic systems except micro-CT.

One limiting factor for clinical application of the FD-VCT system is the lack of variable collimation of the X-ray tube in the prototype used in the study, despite the fact that the CT dose index amounts to $0.172 \text{ mGy mA}^{-1}$, which is comparable to MSCT systems permitted for clinical use. The radiation dose of a CT-examination of the head amounts to 120 mSv, the radiation dose of a dental X-ray is 3 mSv. Accordingly, the radiation dose of a complete FD-VCT evaluation of the head in case of a presumed vertical root fracture is too high, but if radiation dose is minimized drastically by a more localized application of the X-ray beam to the area of interest as in Accuitomo device (Morita), then future clinical applications of the FD-VCT detector technology are feasible for endodontic purposes. This will help to avoid surgical exploration in case of expected vertical root fractures.

The present study investigated root fractures in extracted teeth. Therefore, future studies on FD-VCT should evaluate the influence of the superimposition of hard and soft tissues on image quality. In fact, various organs of different composition and even whole animals have been investigated tomographically with FD-VCT without any artefacts or superimposing structures hampering image quality (Kiessling *et al.* 2004). In any case, the FD-VCT-system offers a broad spectrum of applications in experimental endodontology for three-dimensional and nondestructive evaluation of vertical root fractures and their genesis.

Conclusion

- FD-VCT is a valuable method for non-destructive visualization and exploration of vertical root fractures and cracks in pre-clinical studies on extracted teeth at a high resolution.
- Further developments should combine the high resolution detector systems of FD-VCT with radiation systems that focus the radiation to the area of interest.
- This will allow clinical application of the FD-VCT technology.

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