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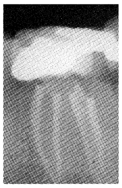

CLINICAL ARTICLE

A preliminary study of the use of peripheral quantitative computed tomography for investigating root canal anatomy

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Abstract

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Aim To evaluate the use of peripheral quantitative computed tomography (pQCT) for qualitative and quantitative analysis of root canal anatomy and for assessing the extent of canal enlargement during root canal instrumentation.

Summary The volume variation achieved by S1 ProTaper instruments in the coronal third of the root canals was analysed using peripheral computed tomography. The tooth was scanned in the horizontal plane producing 36 consecutive cross-sectional images. All images were the result of 360 projections with a section thickness of 250 μm, a distance between slices of 0.5 mm and an in-plane pixel size of 70 × 70 μm. The evaluation was completed before and after S1 ProTaper instrumentation (with or without circumferential filing) of one root canal of a freshly extracted maxillary first premolar tooth. The acquired images were realigned geometrically and processed using a 3D visualization software. pQCT scanning allowed 3D reconstruction of the root canal anatomy and the assessment of the extent of canal enlargement during root canal instrumentation with lateral displacement of canal walls and hence volume change being greater than the coefficient of variation. The densitometry evaluation showed uniform density along the root canal wall.

Key learning points

- pQCT scanning allowed 3D reconstruction of the root canal anatomy and the assessment of the extent of canal enlargement during root canal instrumentation.
- pQCT shows promise for allowing qualitative and quantitative analysis of endodontic procedures.

Keywords: 3D imaging, peripheral quantitative computed tomography, qualitative and quantitative methodology, root canal instrumentation, root canal preparation.

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Introduction

Precise morphological mapping of the root canal system is a prerequisite for the evaluation of endodontic instruments and procedures. A detailed understanding of the root canal system is, in fact, critical for the characterization of all factors that might have a significant impact on the volume of root canals and pulp chambers and in the development of successful therapeutic strategies. Conventional destructive approaches based upon 3D computer-based reconstructions of histological sections do not allow a longitudinal assessment of the endodontic therapy, are limited by the poor precision of the volumetric algorithms, and do not permit a systematic mapping of the endodontic volumes (Walton 1976). Several non-destructive approaches have been developed more recently. For example, computed tomography has been applied extensively to the detection of enamel thickness from an anthropological perspective (Gantt *et al.* 2006), but the available resolution did not allow a precise mapping of the root canal nor the estimation of the canal volumes that were usually overestimated (Gantt *et al.* 2006). The inability of conventional imaging techniques to visualize the root canal system drove the development of alternative imaging modalities. In this context, two procedures have proven to be suitable for the non-destructive exploration of both teeth and the volumetry of the root canals, namely magnetic resonance microscopy (MRM) and X-ray computed microtomography (μCT).

Magnetic resonance microscopy, a high-resolution magnetic resonance spectroscopy system, constitutes a powerful tool for a detailed analysis of teeth without applying ionizing radiation (Tseng *et al.* 2007). However, standard methodologies require a strong proton signal of the surrounding liquid to produce a boundary surface image to visualize the mineralized tissue. Magnetic resonance tomography (MRT) with stray field imaging (STRAFI) (Baumann *et al.* 1993) can achieve this directly, in a very short T2 time, but with poor resolution and the different hard tooth tissue components cannot be differentiated as in the case of MRM. Imaging of all structural components of a tooth with one system and one image was not possible until the demonstration that constant-time imaging (CTI) techniques enabled the detection of magnetic signals from the hard tooth tissues, as well as from the proton- and signal-intensive pulpal tissue. By presenting both signals in one image with a resolution as low as 195 μm, CTI combines the advantages of both the standard MRM and the STRAFI (Appel & Baumann 2002), but it might be limited in the qualitative and quantitative description of the smallest components of the pulpal chamber.

The μCT is a miniaturized form of conventional computerized tomography. The μCT scanner uses an X-ray tube as radiation source and a 3D reconstruction algorithm. Recently, μCT has been introduced to evaluate not only cross-sections of roots but also 3D shapes of canal systems at resolutions as high as 36 μm (Dowker *et al.* 1997, Bjørndal *et al.* 1999, Rhodes *et al.*1999, Peters *et al.* 2000, 2001, Bergmans *et al.* 2001, Gluskin *et al.* 2001, Gao *et al.* 2006, Lee *et al.* 2006). This innovation was achieved because new hardware and software were available to evaluate the metrical data created by μCT, thus allowing geometrical changes in prepared canals to be determined more precisely. This technique has two disadvantages: it is limited to the processing of two extracted teeth at a time because of the small size of the gantry and has a long scanning time up to 6 h (Peters *et al.* 2003). New developments include high-resolution X-ray computed tomography (HRXCT) and flat panel-based volume computed tomography (fpVCT). HRXCT is applied to the 3D reconstruction of enamel thickness, and of dentine and pulp chamber volumes at a resolution ranging from 5 to 100 μm by exporting two-dimensional digitized images obtained by combining modular energy sources (125–450 kV) and modular detectors (Gantt *et al.* 2006). The fpVCT has also been found suitable for the qualitative visualization of the root canal system despite its low spatial resolution of 150 μm. This technique is in fact able to visualize dentine, enamel and the root canal system in 3D-image reconstruction that, because of the size of the gantry (40 cm in diameter), might include several teeth at the same scanning time (Hannig *et al.* 2006).

However, a systematic evaluation of endodontic instruments and procedures based upon these instruments is not practicable, given their high cost and limited availability. Therefore, the following study is designed to evaluate the feasibility of applying peripheral quantitative computed tomography (pQCT) to the qualitative and quantitative analysis of root canal anatomy and for assessing the extent of canal enlargement during root canal instrumentation. pQCT has been originally designed for the diagnosis of osteoporosis in humans, rats and mice (Schmidt *et al.* 2003). The unit works with a specially developed X-ray tube having a minute focal spot whilst the detector system consists of a series of miniature semiconductor crystals. The device is equipped with a special detector collimator that can be switched up to four collimator sizes corresponding to the four section thicknesses (100, 250, 500 and 750 μm). Although the planar resolution of pQCT (70×70 μm) does not have the same resolution as μCT, it might provide a nondestructive morphological investigation at low cost and shorter scanning times.

Materials and methods

Specimen selection and preparation

The study is preliminary in nature, with only one tooth analysed. One root canal of a maxillary first premolar tooth, freshly extracted for clinical reasons and not relating to this study, was selected. After preparing a standard access cavity, the canal was passively negotiated with sizes 10 and 20 K-files to the apical foramen; the working length was determined visually.

Canal preparation was completed by a single operator using Ni–Ti rotary instrumentation; the S1 ProTaper (Dentsply Maillefer, Ballaigues, Switzerland) was mounted on an ATR Tecnika Vision system (motor and handpiece) (ATR, Pistoia, Italy).

For assessing the extent of canal enlargement during root canal instrumentation, two different applications of S1 ProTaper on the coronal third of the root canal were considered: the first in compliance with the manufacturer's protocol and the other arbitrarily modified to produce a loss of the canal wall structure. Therefore, S1 ProTaper was used, for approximately 9 s, until reaching 1 mm from the working length, centering and avoiding any lateral movement (first phase), then applying lateral displacement (second phase) for a further 9 s. The instrumentation was deliberately applied to one side of the root canal system, leaving the other side untreated as a control.

Scanning

Tomographic tooth scanning and measurements were obtained before and after each instrumentation phase.

A pQCT scanner was used for the measurements (Research SA+; Stratec Medizintechnik GmbH, Pforzheim, Germany). This translation rotation scanner works with a specially developed X-ray tube with a 50-μm spot size (high voltage 50 kV, anode current <0.3 mA, mean X-ray energy 37 keV, energy distribution after filtration 18 keV full width half maximum [FWHM]). The detector-system consists of 12 miniature semiconductor crystals with amplifiers. The precision error supplied by the manufacture for density measurement *in vivo* is around 1.5%.

The tooth was scanned in the horizontal plane producing 36 consecutive cross-sectional images at a distance of 0.5 mm.

All images were obtained with 360 projections, with a section thickness of 250 μm and at an in-plane pixel size of 70 × 70 μm at a scan speed of 3 mm s^{-1}. Total scanning time was 4 h. Operator time was limited to 10 min.

Scanning of a selected region of the root canal was also obtained with a section thickness of 100 μm. As no additional information was available, this scanning procedure was aborted.

To orientate the long axes of the tooth parallel to the image planes, the tooth was fixed with manufacturer-made plastic holders. The correct longitudinal positioning was determined by means of an initial scout scan.

Qualitative data analysis

To correct the possible mispositioning of the specimen in the pQCT gantry, the acquired studies were geometrically realigned using a registration technique based on the maximization of mutual information implemented in a home-made software package (Rizzo *et al*. 2005). After registration, the studies corresponded geometrically, with sub-voxel accuracy, and could be compared correctly.

The registered images were then processed using 3D visualization software (amira 4.1; Mercury Computer System Inc., Chelmsford, MA, USA) to generate 3D rendering of the tooth external surface and the root canal, for the qualitative evaluation of the modification of the root canal size, produced by the S1 ProTaper. The coefficient of variation of the reconstructed volumes after repositioning was assessed by performing the quantitative analysis on the actual cross-sections of the root canal that had not undergone to instrumentation. It varied from 3.3% to 7.1%.

Quantitative data analysis

A quantitative assessment of the canal volume variations induced by the instrumentation was carried out using the 3D analysis software 'analyze' (Biodynamic Research Unit, Mayo Clinic, Rochester, MN, USA) (Robb *et al.* 1989). From each registered image, the root canal volume, corresponding to the area of interaction of S1 ProTaper (coronal third of the root canal), was extracted, by calculating, on each slice, the isocontour corresponding to the same isovalue. The volume of the dentine removed was then obtained by subtracting the canal volumes after and before treatments.

Furthermore, a densitometry evaluation was performed, with the pQCT scanner, which directly provided sectional images accurately calibrated in terms of density. Dentine density in each scan was calculated by analyze. For this purpose, densities <500 mg cm^{-3} corresponding to the tooth canal or >2000 mg cm^{-3} corresponding to the tooth enamel were excluded.

Results

Qualitative evaluation

In Fig. 1, the 3D representation of the external tooth surface and the root canal is shown for each study, after spatial registration. From the qualitative analysis it is possible to note the effect of using ProTaper in a lateral displacement mode: the size of the treated canal area is enlarged (see arrow).

The same effect can be seen in Fig. 2, which visualizes the surface of the canals, before and after the treatments. The increment of canal volume is evident when ProTaper is used in a lateral displacement mode (Fig. 2e) but is not noticeable when ProTaper is used more passively (Fig. 2d).

Figure 1 Representative 3D rendering of the external tooth surface and canal for each experimental condition. Left: treatment with K-file 20 instrumentation. Middle: treatment with S.1 ProTaper instrumentation used as protocol. Right: treatment with S.1 ProTaper instrumentation used by lateral displacement. The enlargement of treated area (arrow) is clearly visible in the third situation.

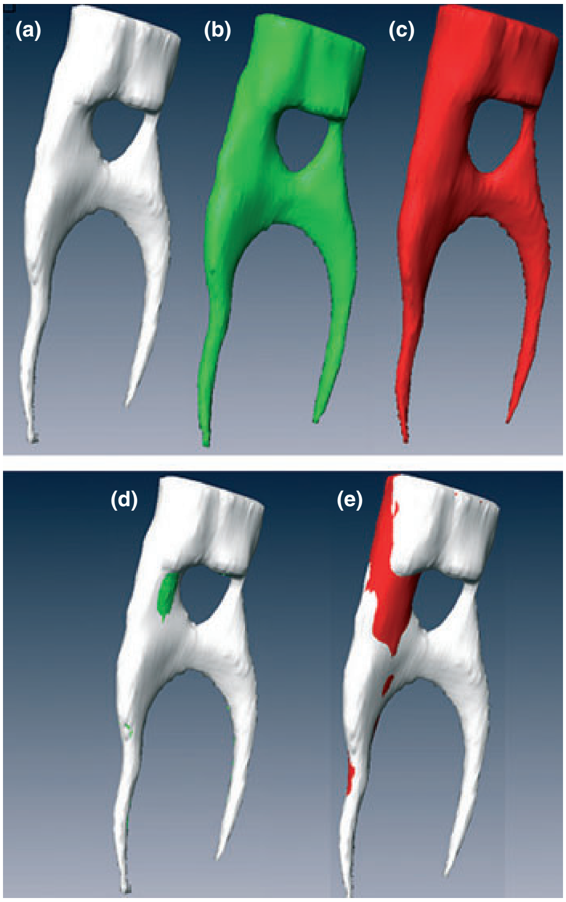

Figure 2 Comparison of 3D rendering of the canal surfaces in different conditions. Top row: (a) K-file 20 (white), (b) S1 ProTaper as protocol (green), (c) S1 ProTaper with lateral displacement (red). Bottom row: (d) superposition of S1 ProTaper as protocol and K-file 20, (e) superposition of S1 ProTaper as lateral displacement and K-file 20. In this last figure, the enlargement of canal using S1 ProTaper as lateral displacement results in an evident red area on the reference K-file 20 white surface.

Quantitative evaluation

Figure 3 shows orthogonal views corresponding to the 3D conditions after registration, with the region of interest (treated area) superimposed as red overlay.

The measured volume sizes for each slice belonging to the treated area are shown in Fig. 4. Lateral displacement produced volume changes far above those detected when ProTaper is used more passively. By applying lateral displacement between the K-file and S1 used in a brushing mode, volume changes ranged from +0.09 mm^3 (38 voxels) in slice

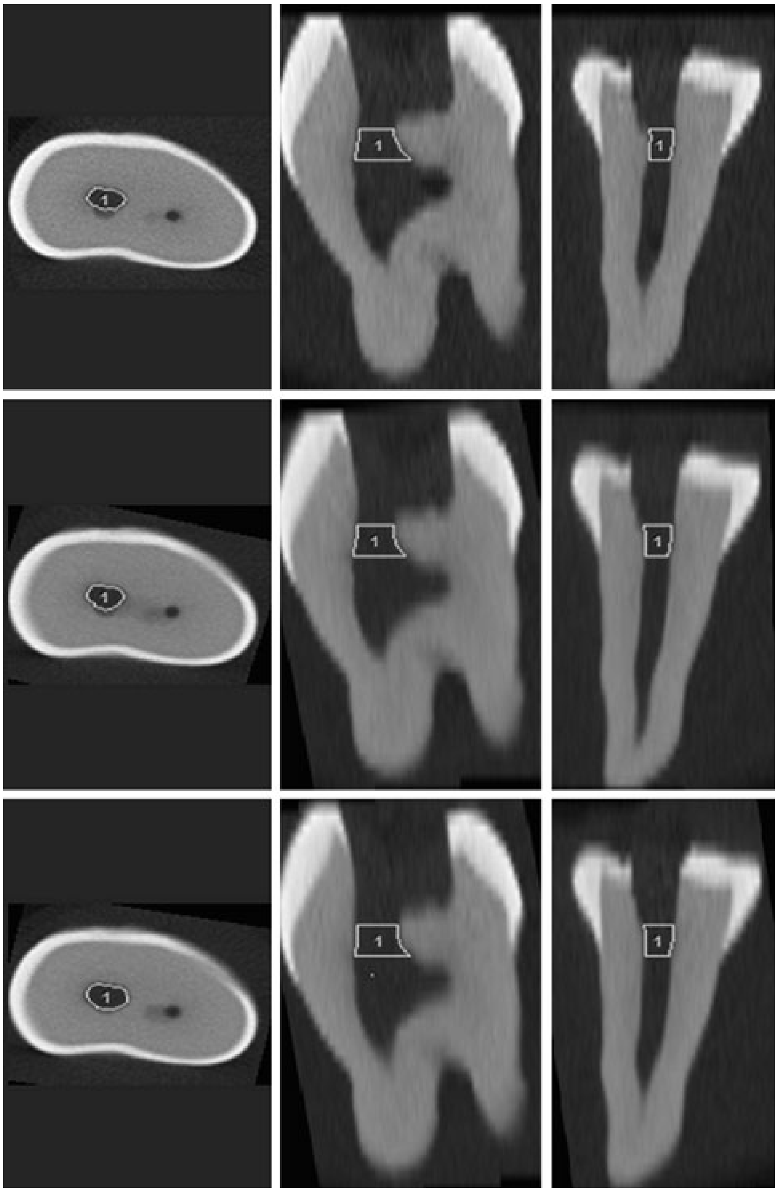

Figure 3 Tooth cross-sectional views corresponding to the three different experimental conditions. Top row: treatment with K-file 20. Middle row: treatment with S1 ProTaper used as protocol. Bottom row: treatment with S1 ProTaper used as lateral displacement. The red overlay corresponds to the treated area.

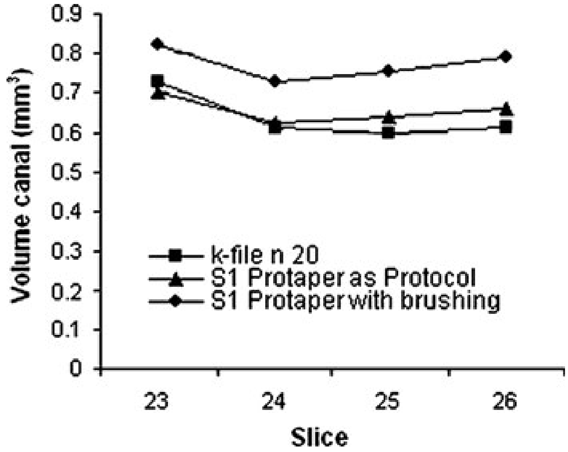

Figure 4 Comparison of tooth canal volumes in the three different experimental conditions. Volumes were measured in all the slices belonging to the treated area (slice 23–26, total longitudinal extension: 2000 μm).

23 to +0.18 mm^3 (72 voxels) in slice 26, whereas without lateral displacement volume changes ranged from −0.030 mm^3 (or 12 voxels) in slice 23 to +0.049 mm^3 (or 20 voxels) in slice 26.

The measured volume sizes for the reconstructed treated area were 2.56 mm^3 before S1 ProTaper, 2.63 mm^3 after S1 ProTaper without lateral displacement, and 3.10 mm^3 after S1 ProTaper with lateral displacement. This resulted in an increment of 2.66% of the canal volume when ProTaper was used more passively, and in an increment of 21% when lateral displacement was applied. Whilst the former increment was in the range of the coefficient of variation, as assessed on the root canal not undergoing to instrumentation (3.3–7.1%), the latter was far above. As not more than one tooth was used, no significant statistical calculation can be presented.

The cross sectional densitometric analysis was able to identify the dentinoenamel junction that was represented in Fig. 5. The density distribution pathway clearly distinguished dentine density from enamel. The longitudinal densitometric analysis globally shows no differences in the density of dentine: as illustrated in Fig. 6, the profile is flat and only small density gradients can be observed for the first curve points, principally because of partial volume effects induced by slice thickness.

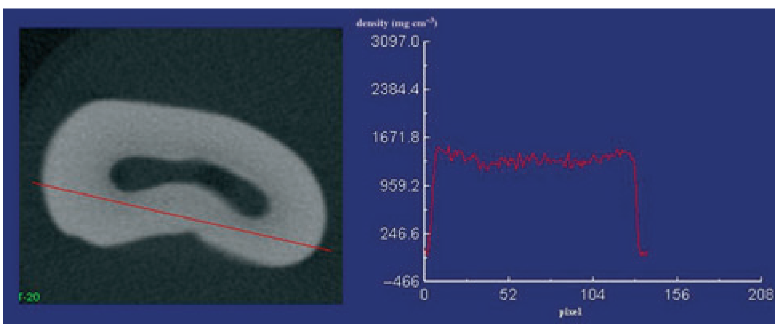

Figure 5 Typical cross-sectional density profile showing the density of the enamel and dentine. The abrupt drop in the density profile corresponds to the dentinoenamel junction.

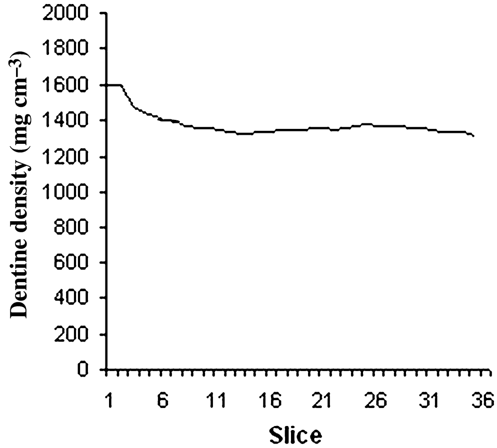

Figure 6 Dentine density measured in the scan correspond to K-file 20 treatment. Slices 1 and 36 are not considered, as they contain very few voxels of dentine.

Discussion

The study has shown that pQCT instruments, developed for bone mineral analysis and having a spatial resolution of 70 × 70 × 250 μm, show promise for allowing a precise and reliable mapping of the root canal system by producing contiguous slices of teeth. The 3D-image reconstruction and the measurements of volumes and densities obtained by pQCT scanning appear to be suitable for the qualitative and quantitative assessment of the changes in root canal shape following instrumentation. The application of a pQCT system to endodontic imaging offers advantages over current NMR and μCT techniques, mainly relating to its lower cost and wider availability, whilst scanning time is only marginally reduced (4 h vs. 6 h). pQCT allows direct visualization of tooth tissues, i.e. dentine, enamel and root canal system, which are clearly distinguishable in the 3D images, and can determine the impact of spatial distribution of the dental volumetric density (enamel versus dentine) on dental pathology. This has not been systematically evaluated and offers potential advantages on our current understanding of the genetic and environmentally related differences in dentine signalling that could alter enamel structure with an impact on dental health. A minor advantage of pQCT is related to its large scanner gantry opening (9 cm) that can include several teeth at the same scanning time as fpVCT (Hannig *et al.* 2006), whereas μCT systems can allow evaluation of two teeth only (Peters *et al.* 2001). The acquired data at each repositioning were realigned geometrically before comparison using a registration technique based on the maximization of mutual information implemented in a home-made software package (Rizzo *et al.* 2005). As the registered sections were geometrically aligned with sub-voxel accuracy, the comparisons should be considered precise and reliable. The detection of volume changes at the side of the root canal system, only where they were expected to be found after adequate instrumentation, sustains a potential application of the developed methodology in the clinical setting. When pQCT, μCT and histomorphometry were compared, the results showed that a pQCT scanning at 500-μm thickness can yield satisfactory precision and accuracy in microstructural representation of the scanned bone site (Schmidt *et al.* 2003). The highest agreement was found between pQCT and μCT being based on the measurement of the same physical property as X-ray absorption.

However, a rigorous analysis of the limits of the pQCT in reconstructing small canals should be outlined. The larger pixel size (70 × 70 μm), and the consequent lower resolution of the pQCT versus μCT, introduces larger partial volume effects that might affect the volumetric evaluation of the pulp chamber and root canals as well as the definition of the dentinoenamel junction and the derived parameters as density. Even if the object of theoretical correction (Rittweger *et al.* 2004), this limitation is critical and is applied when projecting a continuous object on a discrete grid. Hence, quantitative image analysis is prone to errors where the edge of the object is within the sampling grid. The segmentation process can overestimate sharp edges depending upon the voxel volumes as the partial volume effect increases with voxel size (i.e. at lower image resolution) and decreases with the object size. This implies that side and/or accessory canals as well as main canals smaller than the voxel size are not detectable with sufficient accuracy, thus hampering correct visualization and analysis. The spatial resolution of the pQCT methodology applied is critical to the reliability of volume change measurements. It is generally accepted that half voxel size for each voxel forming the volume surface contributes to the uncertainty range in volume estimate, because of spatial resolution. It follows that, in the case of the root canal system, the uncertainty varies along the canal and is related to its size. By approximating to a cylinder the shape of the root canal represented in a single tomographic slice, the measurement uncertainty of the volume changes observed should be expected ranging from 10% to 11% (from 28 to 31 voxels) for canal volume ranging from 250 to 298 voxels (slices 23–26). This quantitative analysis suggests that the volume changes observed when lateral displacement was applied were reliable and, as a consequence, lateral displacement should be avoided to preserve optimal mechanical strength of tooth. In fact, the potential for the root filled teeth to fracture increases proportionally with the amount of dentine removed (Pilo *et al.* 1998).

Conclusion

This study has presented an innovative and nondestructive methodology to illustrate canal morphology and canal volume changes after instrumentation by applying pQCT analysis. The 3D reconstruction methodology based on pQCT images described here deserves further systematic evaluation to fully validate its application in the clinical setting as a tool for qualitative and quantitative analysis of the endodontic procedures.

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