The imaging of root canal obturation using micro-CT

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Abstract

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Aim To examine the potential and accuracy of micro-computed tomography (micro-CT) for imaging of filled root canals.

Methodology The root canals of five extracted maxillary teeth were shaped manually with K-files. After irrigation and drying, the root canals were filled by lateral condensation using gutta-percha cones and AH plus (Dentsply Maillefer, Ballaigues, Switzerland) as sealer. The filled root canals were examined by micro-CT at resolutions <11 μm. Three-dimensional reconstructions of the root canal fillings were made. The roots were sectioned histologically and standard photographs of the sectioned surfaces were taken. Digitized photographic images and the corresponding micro-CT sections were correlated qualitatively by superimposition. Quantitative morphometric data were obtained with respect to the surface area of the root canal filling and the individual gutta-percha points of the histological and the micro-CT sections. Pearson correlation coefficients were calculated.

Results There was a good qualitative correlation between the images from the histological and the micro-CT sections. The fillings were clearly differentiated from the root canal walls. Individual gutta-percha cones and sealer were discernable. Pearson correlation coefficients showed a highly significant correlation between the two methods ($P < 0.001$) with respect to the area of the complete root canal filling ($r = 0.992$) and the gutta-percha cones ($r = 0.968$).

Conclusions The micro-CT technique was a highly accurate and nondestructive method for the evaluation of root canal fillings and its constituents. Qualitative and quantitative correlation between histological and micro-CT examination of root canal fillings was high.

Keywords: imaging techniques, micro-computed tomography, root canal filling, root canal obturation.

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Introduction

High resolution micro-computed tomography (micro-CT) is an emerging technology with several promising applications in different fields of dentistry. Early studies using traditional CT technology for the examination of teeth were compromised by limited vertical resolution capacity of 1–2 mm and were impaired by attenuation of X-rays by metallic substances. Low resolution of conventional CT was insufficient for adequate reconstruction of small objects such as teeth or root canals (Tachibana & Matsumoto 1990, Nielsen *et al.* 1995). The development of micro-CT increased the vertical resolution capacity to 100–200 μm (Nielsen *et al.* 1995, Bjørndal *et al.* 1999). In recent years resolution of micro-CT was further improved to 81 μm (Rhodes *et al.* 1999) or to resolution values between 34 and 68 μm (Dowker *et al.* 1997, Peters *et al.* 2000, Gluskin *et al.* 2001), to 25 μm (Verdonschot *et al.* 2001) and 15 μm (Verna *et al.* 2002). At present, axial scanning steps of <10 μm are possible.

Micro-CT has been used as a research tool in various applications. Among these is the evaluation of trabecular bone structure (Müller *et al.* 1998), membranous bone (Buchman *et al.* 1998) and bone tissue around

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oral implants or grafted periosteum (Ueno *et al.* 1999, Van Oosterwyck *et al.* 2000, Jung *et al.* 2003). Healing patterns of bone defects and morphometric evaluation of periapical bone destruction have been studied by micro-CT (Balto *et al.* 2000, Verna *et al.* 2002, Von Stechow *et al.* 2003). The accuracy of micro-CT with respect to periapical bone destruction has been evaluated by correlating histological sections and the micro-CT images (Balto *et al.* 2000). Enamel thickness and the hard tissue macromorphology in molars have been investigated (Spoor *et al.* 1993, Nielsen *et al.* 1995, Bjørndal *et al.* 1999) and a three-dimensional (3-D) finite element model of a premolar has been developed with the help of micro-CT (Verdonschot *et al.* 2001).

With respect to experimental endodontology, micro-CT proved to be a valuable method (Rhodes *et al.* 1999). Root canal geometry (Nielsen *et al.* 1995, Dowker *et al.* 1997, Peters *et al.* 2000) and the effect of instrumentation on root canal morphology have been assessed by several studies (Nielsen *et al.* 1995, Rhodes *et al.* 1999, Bergmans *et al.* 2001, Gluskin *et al.* 2001, Peters *et al.* 2001, 2003).

The micro-CT technique has numerous advantages. The method is rapid and noninvasive. The results are reproducible and comparable with histology (Balto *et al.* 2000, Von Stechow *et al.* 2003). Morphometry of bone, connective tissue, teeth or root canals are the possible applications (Balto *et al.* 2000, Giesen & Van Eijden 2000, Peters *et al.* 2000, Von Stechow *et al.* 2003). Micro-CT can show changes over time with respect to surface area and volume of tissues (Nielsen *et al.* 1995).

However, *in vivo* application of the micro-CT technique is subjected to various limitations. Other problems relate to the choice of segmentation threshold values, which may influence the appearance of objects of interest. Segmentation of different objects, tissues or materials is obvious if there are large differences in the attenuation characteristics of the various objects (Peters *et al.* 2000). It has been demonstrated that the segmentation of closely related objects such as different dental hard tissues, calcified tissues and root canal filling material is possible (Nielsen *et al.* 1995).

In the field of endodontic research, micro-CT technology is frequently used for the evaluation of root canal anatomy and for the assessment of root canal morphology after instrumentation. There are only two examples of obturated root canals being investigated by micro-CT (Nielsen *et al.* 1995, Dowker *et al.* 1997). Detailed micro-CT evaluation of endodontic obturation and the accuracy of this method for the evaluation of root canal fillings have not yet been described.

The primary aim of the current study was to compare the results of imaging of obturated root canals using micro-CT with conventional histological sections qualitatively and quantitatively. The secondary aim was to assess whether 3-D reconstruction of the complete root canal filling and its components was possible.

Materials and methods

Sample preparation

Four single rooted maxillary teeth that had been extracted for periodontal reasons were used for the comparison between micro-CT and histological sections. The teeth composed of two central incisors, one lateral incisor and a second premolar. For the 3-D reconstruction, a maxillary first premolar was used (Table 1). After preparation of an endodontic access cavity, working length for each tooth was determined radiographically. The root canals were shaped with hand instruments (K-files; VDW/Antaeos, Munich, Germany) using a step back technique. After irrigation with H_2O_2 and NaOCl, the canals were dried. AH plus (Dentsply Maillefer, Ballaigues, Switzerland) was applied as a sealer and the root canals were obturated with a gutta-percha master point size 40 (tooth 11 and 21), 45 (tooth 12 and 25) and 35 (tooth 24). Cold lateral condensation was performed using size 20 CC Cord finger spreaders (VDW/Antaeos) and correspondingly sized gutta-percha accessory points. Quality of the root canal filling was assessed radiographically and access openings were sealed with glass–ionomer cement. The teeth were then stored at a relative humidity of 100% for at least 4 weeks.

Because of the limited dimensions of the micro-CT chamber, the coronal part of each tooth was separated from the root approximately 1 mm coronal to the

Table 1 Specification of the teeth and the details of root canal treatment

Tooth	Working length (mm)	MAF size	FF size	Masterpoint size
11	22.5	35	50	40
12	20	40	55	45
21	23	35	50	40
25	21	40	55	45
24	25/25	30/35	45/45	30/35

FF: final file.

cemento-enamel junction. The sectioned surface of each root was fixed on a 10 mm × 10 mm plastic plate and was embedded with Palapress resin (Heraeus Kulzer, Wehrheim, Germany).

Micro-CT examination

The samples were examined using the high-resolution micro-CT system SkyScan 1072 80 kV (SkyScan, Aartselaar, Belgium). The X-ray source was an air-cooled, sealed microfocus X-ray tube with a focal spot size <8 μm. The X-ray tube was operated at 80 kV and 100 μA (0.5 mm Al filter). The X-ray detector consisted of a 1024 × 1024 pixel 12-bit CCD camera with fibre-optic coupling to an X-ray scintillator. An automatic filter changer for beam-hardening compensation during reconstruction was used at a level of 25%. The system was controlled by a PC workstation running under Microsoft Windows XP Professional. Scanning of the specimens was done with a 180° rotation around the vertical axis and a single rotation step of 0.9°. The cross-sectional pixel size and the cross-section/cross-section distance were 6.98 μm (tooth 11, 12, 21 and 25) and 11 μm (tooth 24). The reconstruction algorithm was the cone beam mode (Johnson *et al.* 1998) and the reconstruction time was 4.7 s per cross-section.

Histological examination

For verification of the micro-CT results, the four single-rooted samples were prepared for histological evaluation. Beginning at the apex, the filled roots were sectioned horizontally using a diamond-encrusted, water-cooled 0.2 mm band saw (Exakt Trennschleifsystem; Exakt Apparatebau, Norderstedt, Germany). The sections were made at a distance of 0.7 mm between two slices. With this procedure, eight to 12 slices were obtained from each of the four obturated roots. The slices were imaged with the microscope SMZ-2T (Nikon Corporation, Tokyo, Japan) at a twofold magnification. Two photographs were made from each slice, one showing the top and one showing the bottom of each slice (OM2; Olympus Corporation, Tokyo, Japan). Subsequently, the photographs were digitized. The slices were examined by SkyScan 1072 and the first micro-CT cross-section from the top and from the bottom of each slice that provided a complete reconstruction of the root surface was used for the comparison. Both the digitized photographs of the sectioned surfaces and the micro-CT sections were imported into an image software program (Corel Draw 10.0; Corel Inc., Dallas, TX, USA). After correlating the magnification of the microscopic and the micro-CT images, the images of the histological sections were transformed into a transparent condition. Subsequently a superimposition of the histological and the micro-CT sections was performed and the images were rotated until the best possible matching was achieved. The degree of correspondence was evaluated qualitatively. Correspondence was rated as 'good', if there were no apparent visual differences after superimposing the micro-CT and the histological images.

For quantitative assessment of correlation, the histological and the micro-CT images were evaluated morphometrically with the help of the image analysis software Analyze 5.0 (Analyze Direct, Lenexa, KS, USA). Surface areas of the whole root filling and dimensions of single gutta-percha points were determined on each section. From these data, correlation coefficients were calculated (SPSS for Windows, version 11.5.1; SPSS Inc., Chicago, IL, USA).

3-D reconstruction

From the data of the micro-CT examination, a cone-beam 3-D reconstruction of the root canal filling of tooth 24 was made with the help of 3D-Calculator software (V. 0.9 Release 2; SkyScan) and Analyze 5.0. Based on grey-level differences, gutta-percha cones and sealer were segmented from each other and the complete root canal filling and sealer were reconstructed separately.

Results

Qualitative correlation

With respect to the four samples investigated, good correlation was observed between the images obtained after histological sectioning and after micro-CT examination. Figures 1–3 show representative examples from various parts of the root canals, demonstrating a good matching of the corresponding images. All details such as master or accessory gutta-percha cones, sealer, recesses or voids were represented both in the histological and the micro-CT images.

Figure 1 shows the micro-CT and the histological sections from the coronal third of the filled root canal of the second maxillary premolar. On both images the circumference of the root canal is distinctly delineated. The gutta-percha master point is discernable on the left

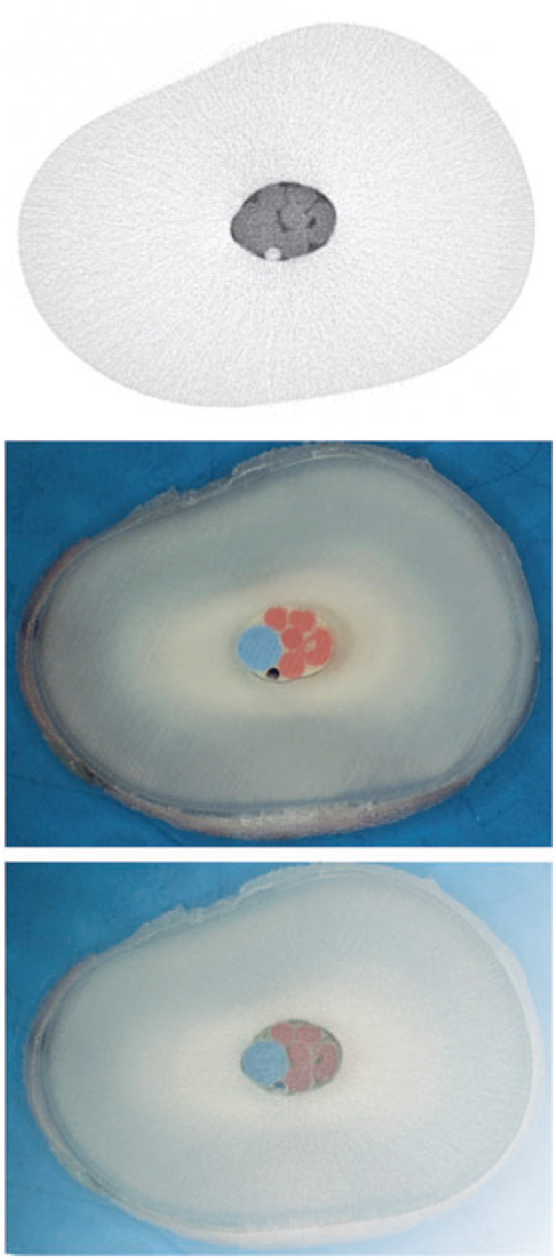

Figure 1 Micro-computed tomography (top) and histological sections (middle) from the coronal third of an obturated root-canal of a maxillary second premolar; superimposition of the two images (bottom).

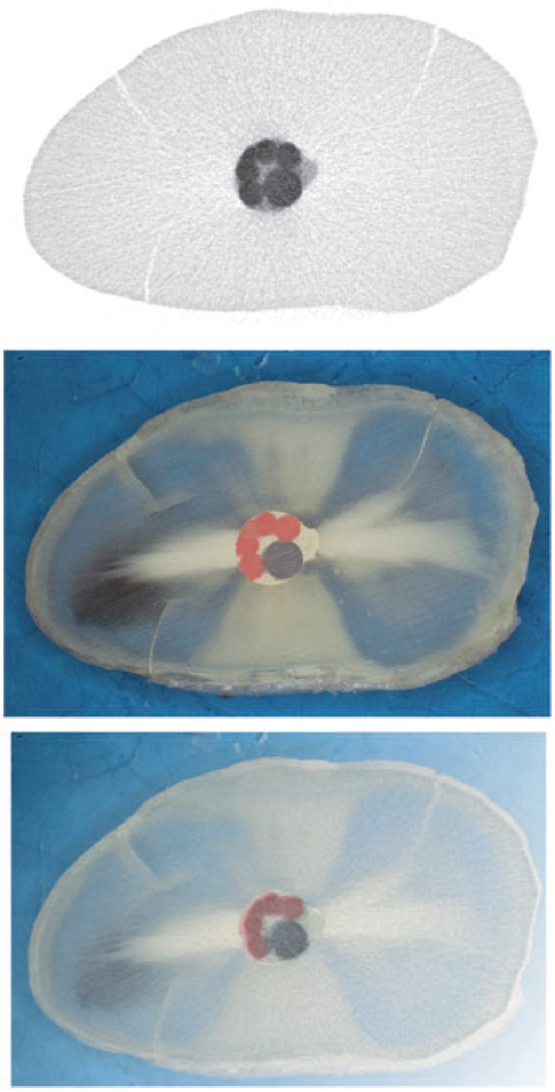

Figure 2 Micro-computed tomography (top) and histological sections (middle) from the middle part of an obturated root-canal of a maxillary central incisor; superimposition of the two images (bottom).

part of the filled root canal in Fig. 1. Four round auxiliary gutta-percha cones and a kidney-shaped accessory point can be discriminated. The space between the points is filled by sealer. A void near the lower circumference of the canal is encased by sealer (Fig. 1, top and middle). The superimposition of the two images (Fig. 1, bottom) shows a good matching of the details of the two images.

The middle third of the filled root canal of a left central maxillary incisor is shown in Fig. 2. The complete circumference of the root canal is filled. The master point contacts the wall of the root canal at the lower circumference (Fig. 2, top and middle). Four accessory cones with round contours are visible. One smaller oval auxiliary point is delineated more clearly

Figure 3 Micro-computed tomography (top) and histological sections (middle) from the apical third of a root-filled maxillary central incisor; superimposition of the two images (bottom).

in the micro-CT image. A large portion of sealer obturates the right part of the canal. The superimposition of the images underlines the good correspondence (Fig. 2, bottom).

Figure 3 depicts a section through the apical third of the filled root canal of a right maxillary central incisor. The master point is located centrally in the root canal. One auxiliary cone is discernable on the right part of the root canal in Fig. 3 (top and middle), creating a concave impression on the circumference of the master point. Only a small portion of sealer is surrounding the two gutta-percha points. There is a bulge of sealer filling an irregularity of the canal curvature on the left side of the root canal in Fig. 3. The superimposition of the two images (Fig. 3, bottom) demonstrates a good matching of the various details.

Quantitative correlation

There was a high correlation of the surface area of the complete root canal filling with respect to histological and micro-CT images. Thirty sections were analysed. Depending on the level of the sections in the coronal, middle or apical third of the root canal, the data for the surface area of the whole root canal filling varied between 0.1 and 2.74 mm^2 (Fig. 4a). Pearson correlation coefficient for the results of histological and micro-CT images was 0.992. The average difference of surface area data between histological and micro-CT sections showed that the bias was very low (−0.004). Standard deviation of the differences (reproducibility) was 0.16 mm^2 (Fig. 5a).

The results for the surface area of the single gutta-percha cones showed a slightly greater variation between histological and micro-CT evaluation (Fig. 4b). Forty-eight gutta-percha cones from 30 sections were analysed and the data for the surface area of the gutta-percha cones varied between 0.04 and 0.71 mm^2. Pearson correlation coefficient was 0.968. The average difference of surface area data between histological and micro-CT sections with respect to gutta-percha cones showed that the bias was low (−0.0162). Standard deviation of the differences (reproducibility) was 0.041 mm^2 (Fig. 5b).

3-D reconstruction

Figure 6 shows the reconstruction of the root filling of the first maxillary premolar. The distal projection (upper row, left image) of the complete filling demonstrates that the buccal portion of the filling has a distinct palatal inclination and that the palatal portion of the obturation is shorter with only a slight inclination. From a palatal projection, the division of the palatal portion of the filling into two separate parts can be observed. From a mesial projection, the buccal portion of the filling appears rather homogeneous,

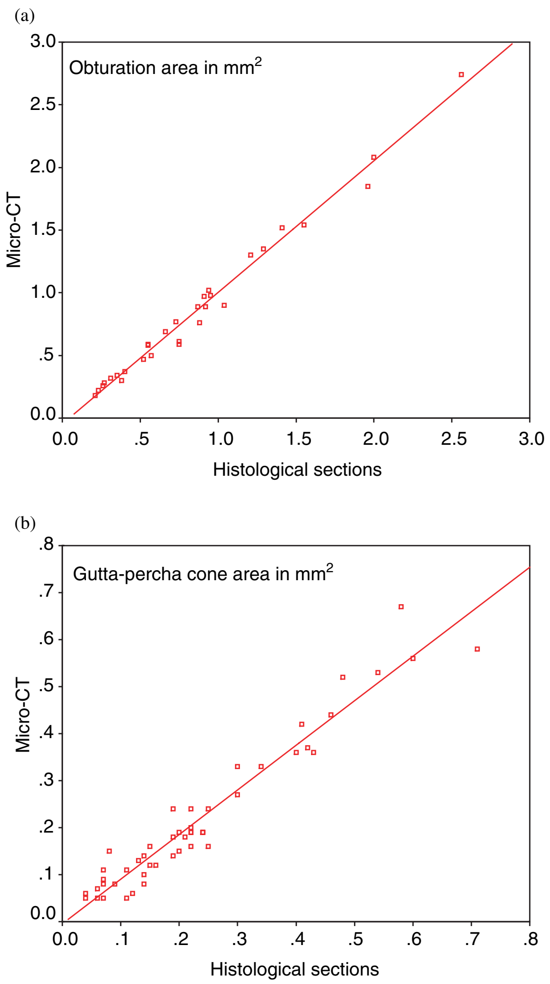

Figure 4 Scatterplot with regression line of surface area of root canal filling (a) from $n = 30$ sections and of gutta-percha cones (b) from $n = 48$ cones from 30 sections with respect to histological sections and micro-computed tomography.

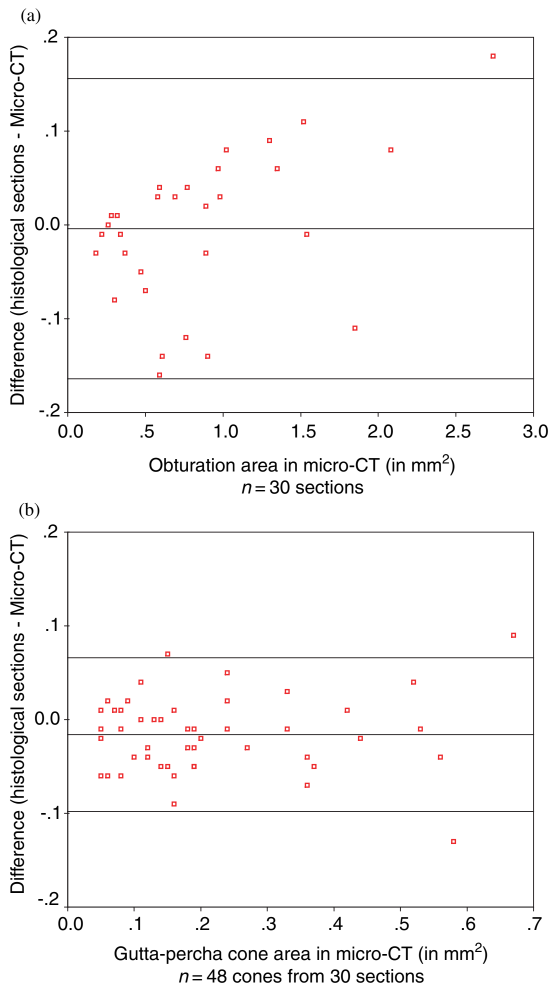

Figure 5 Bland & Altmann (1986) scatterplot of surface area of root canal filling (a) and gutta-percha cones (b) in micro-computed tomography (micro-CT) and differences of surface area of corresponding histological and micro-CT sections; reference lines represent bias (middle line) and reproducibility (bias ± 2 SD, upper and lower line) as 95% tolerance interval for differences.

whilst the palatal portion shows some irregularities along the outer curvature. This observation is confirmed in a disto-buccal projection. Additionally, the buccal portion of the filling shows a groove in the middle third.

The corresponding projections of a separate reconstruction of the sealer constituents of the filling are shown in the bottom row of Fig. 6. Separate portions of sealer are irregularly distributed along the course of the root canal. The irregularities in the middle third of the palatal portion of the filling, which were described above, turned out to be filled by sealer. The greatest coherent amount of sealer in the buccal portion of the filling is located in the middle third.

Discussion

Achieving a high-quality root filling is one prerequisite for the success of root canal treatment (Petersson *et al.* 1986). Several methods are used to assess the quality of root fillings: leakage studies employing dye or alternative tracers comprise a large part of endodontic research (Wu & Wesselink 1993). Conventional leakage studies are more or less destructive by using vertically (Clinton & Himel 2001, Imai & Komabayashi 2003) or horizontally (Gençoglu *et al.* 2002) sectioned surfaces

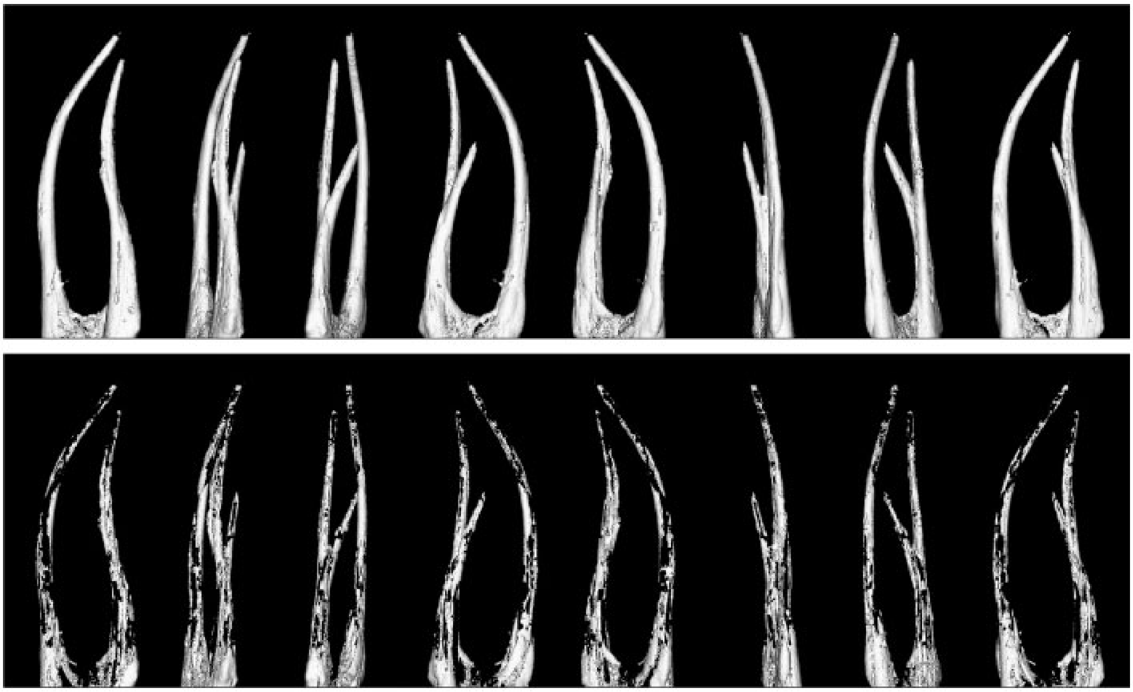

Figure 6 3-D reconstruction of the root canal obturation of a maxillary first premolar after micro-CT examination; complete filling (top) and separate reconstruction of sealer (bottom); 48° viewing angle between the projections, starting from a distal view.

of filled canals for the quantification of leakage. Because of various shortcomings, conventional leakage studies provide only limited information (Wu & Wesselink 1993, Pommel *et al.* 2001). Little correlation was found between the results of apical dye leakage studies and clinical success (Oliver & Abbott 2001). Moreover, results of leakage studies are frequently characterized by semi-quantitative data. Quantitative volumetric data are regarded to be more pertinent (Wu & Wesselink 1993). With the help of the fluid-filtration method, leakage is assessed indirectly by the movement of an air bubble in a capillary glass tube (Cobankara *et al.* 2002, Pommel *et al.* 2003). Wu *et al.* (1993) described another modification, the fluid transport model. Other techniques for the evaluation of root canal fillings include histological sectioning of filled canals and subsequent evaluation of voids or sealer distribution by image analysis (Gani *et al.* 2000, Wu *et al.* 2000, Wu & Wesselink 2001, Hembrough *et al.* 2002). Creating transparency of root dentine by decalcification and application of methylsalicylate is an alternative for assessing the quality of filling (Villegas *et al.* 2002, Venturi *et al.* 2003). The density of root fillings is evaluated indirectly by weighing (Gound *et al.* 2001, Deitch *et al.* 2002) or by the amount of spreader penetration (Bal *et al.* 2001). In some cases, radiography was used for assessing the adequate filling of root canals (Goldberg *et al.* 2001, Estrela *et al.* 2002). Recently, a nondestructive *in vitro* method for imaging and quantification of bioluminescent bacteria in root canals has been described (Sedgley *et al.* 2005). This could be a promising approach for leakage studies.

The micro-CT technique could help to overcome some of the disadvantages of the methods generally used to assess root canal obturation as it is nondestructive. The current study shows that it is possible to distinguish between sealer, gutta-percha cones and voids. With the help of a 3-D reconstruction, information about the complete filling and about the distribution of the components of a root canal filling can be obtained.

When evaluating micro-CT images, beam-hardening effects should be taken into account. These artefacts are a result of the polychromaticity of the X-ray source and can cause visual distortions of the reconstructed images such as edge enhancement of the objects. A correction of beam hardening artefacts can cause a decrease in image quality (Van de Casteele *et al.* 2004). Nevertheless in order to minimize these effects, a beam hardening compensation was performed during reconstruction.

From the results of this study, it cannot be predicted whether it will be possible to quantify leakage with the help of micro-CT. Volumetric leakage evaluation might be facilitated by use of a tracer that can be segmented from the constituents of the root canal obturation.

Micro-CT offers the possibility of repeated scanning. Thus, it will be possible to evaluate changes of filling over time.

With respect to gradual changes of root canal anatomy in the *z*-direction, Peters *et al.* (2000) believed that a resolution of 34 and 68 μm would be sufficient for endodontic micro-CT studies. In the current study, root canals were scanned at a resolution of <10 μm for the first time. Owing to its large size (length of 25 mm), scanning of tooth 24 was only possible at a resolution of 11 μm. The advantage of such a high resolution is a greater accuracy of the rendered images. On the other hand, the amount of data and the scanning time were increased. In order to obtain detailed information about small objects such as auxiliary gutta-percha cones, sealer thickness or the presence of voids or lateral canals, a high resolution seems to be advantageous.

The quality of the 3-D reconstruction of root filling and sealer is determined by the spatial resolution and the grey-level spectrum of the micro-CT system. It is difficult to compare spatial resolution of the micro-CT and sealer film thickness, because numerical data about sealer cement thickness vary considerably. Different filling techniques caused sealer film thickness from 2.2 to 47.6 μm. Lateral compaction yielded a sealer thickness of 11.1 μm (Weis *et al.* 2004). With conventional measurements using glass slides under load (McMichen *et al.* 2003), film thickness varied from 110 μm for Tubli-Seal EWT (Kerr, Romulus, MI, USA) to 440 μm for AH Plus. In the present study tooth 24 was scanned at a resolution of 11 μm. This would be in the numerical range of the data reported by Weis *et al.* (2004) and indicates that high resolution for micro-CT scanning might be essential for this purpose.

The current quantitative data showed that there was a higher correlation between the results of micro-CT and histological sections with respect to the surface area of the complete root canal filling compared with the correlation of the single gutta-percha cones. One of the image pairs of corresponding histological and micro-CT sections indicated that the micro-CT images rendered a more detailed separation of auxiliary gutta-percha cones. Limitations of the histological sectioning may have compromised the differentiation of small objects.

It is a disadvantage that the micro-CT technique has limitations with respect to *in vivo* applications. The use of micro-CT is confined to the examination of specimens of limited size. *In vivo* scanning of animals is possible at resolutions similar to those described in the present study. Digital volume tomography (DVT) is a recent development which may have clinical indications in the field of maxillofacial surgery (Ziegler *et al.* 2002, Erickson *et al.* 2003). DVT permits *in vivo* skull imaging and 3-D reconstruction with high geometric accuracy at a low radiation dose. At present, the low resolution from 0.1 to 0.3 mm limits the application of this technique for clinical endodontic purposes.

Conclusions

With respect to imaging of root canal fillings, histological and micro-CT sections showed a good qualitative correlation. The constituents of a root canal filling, such as gutta-percha cones and sealer could be discriminated using the micro-CT technique.

3-D reconstruction of the root canal filling and its constituents is possible. The micro-CT technique is a highly accurate and nondestructive method for the evaluation of root canal fillings *in vitro*.

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