RESEARCH ARTICLE

Imaging of root canal treatment using ultra high field 9.4T UTE-MRI – a preliminary study

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Objectives: To investigate the potential of 9.4T ultrashort echo time (UTE) technology visualizing tooth anatomy and root canal treatment *in vitro*. In particular, it was evaluated whether the currently achievable resolution is suited presenting all anatomical structures and whether the root canal filling materials are distinguishable in UTE-MRI.

Methods: Four extracted human teeth were examined using 9.4T UTE-MRI prior endodontic treatment (native teeth), after preparation and after obturation procedure. Root canal obturation was performed using warm vertical compaction (Schilder technique) with an epoxy-resin-based sealer. A single gutta-percha cone measured by MRI served as intensity-reference. MRI results were validated with corresponding histologic sections of the teeth. In addition, all teeth were examined at the different stages with CBCT and conventional X-ray.

Results: 9.4T UTE-MRI enabled a precise visualization of root canal anatomy of all teeth at a resolution of 66µm. After obturation, dentin, sealer and gutta-percha cones showed distinct MRI signal changes that allowed clear differentiation of the obturation materials from surrounding tooth structure. The filling materials, isthmal root canal connections and even dentin-cracks that were identified in the MR-images could be verified in histological sections.

Conclusions: 9.4T UTE-MRI is suitable for visualization of root canal anatomy, the evaluation of root canal preparation and obturation with a high spatial resolution and may provide a versatile tool for dental material research in endodontics.

Dentomaxillofacial Radiology (2020) 49, 20190183. doi: [10.1259/dmfr.20190183](https://doi.org/10.1259/dmfr.20190183)

Cite this article as: Timme M, Masthoff M, Nagelmann N, Masthoff M, Faber C, Bürklein S. Imaging of root canal treatment using ultra high field 9.4T UTE-MRI – a preliminary study. *Dentomaxillofac Radiol* 2020; 49: 20190183.

Keywords: dental MRI; endodontics; obturation; root canal filling; root canal preparation

Introduction

Recently, MRI has undergone major technical developments that have considerably expanded its indications. Thus, dental imaging has been presented as a field of application.^{1–3} MRI supplies both a high soft tissue contrast and a high spatial resolution.⁴

However, imaging of hard tissues like bone or teeth is still challenging due to their limited water content.⁵ As a result, only sequences sensitive to ultrashort

T2-relaxation can be used to analyze these tissues at relatively high spatial resolution and with a high signal to noise ratio. Recently, the zero-echo-time and the ultrashort-echo-time sequences were introduced for this purpose. These sequences have already been applied in dental imaging.^{5–7} The appearance of the different tooth structures, the detection of carious lesions and the visualization of restorative materials were investigated.^{8,9} The main disadvantages of MRI include limited availability, high acquisition and maintenance costs of the devices, long exposure times and susceptibility to

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Received 08 May 2019; revised 09 September 2019; accepted 10 September 2019

artifacts. In particular, metallic dental restorations and dental implants may lead to pronounced artifacts.¹⁰

Numerous fields in endodontics, like root canal anatomy and geometry, various methods of root canal preparation or obturation, are of scientific interest.¹¹ Therefore, various radiological techniques (periapical radiographs, CBCT, μ -CT, nano-CT) are suitable in these investigations.^{12–14} The golden standard for visualization of structures inside a tooth is histological sectioning.¹⁵ Nevertheless, sectioning is accompanied with the destruction of the sample and is therefore excluded for various purposes.

Therefore, development of new non-destructive imaging techniques using the strengths of non-invasive and radiation-free MRI would be desirable.¹ In this preliminary study, we aimed to evaluate the use of UTE-MR-imaging for 3D visualization of root canal anatomy before and after chemo-mechanical root canal preparation and MRI for visualization of obturation and its components. Focus was set on the achievable resolution and the potential of UTE-MRI to distinguish root canal filling materials.

Material and methods

Teeth

In this preliminary study, four exemplary human teeth with a complex root canal anatomy or other irregularities were selected: a maxillary molar, two mandibular molars and a mandibular premolar. The premolar presented an apical hypercementosis. None of the teeth had a visible carious lesion or other defects. Teeth presenting carious lesions, resorptive defects, restorations, fillings or root canal fillings or avitality were excluded. All teeth came from different patients and were extracted for periodontal indication. All patients agreed to scientific use of their extracted teeth. All teeth were placed in physiological NaCl solution after extraction at 4°C. All teeth underwent further assessment at three stages: i) native teeth ii) after root canal preparation iii) after obturation procedure.

Root canal preparation and obturation

Teeth were accessed using diamond burs and a straight-line access was achieved. The working length was obtained by measuring the length of the instrument used for patency check (size 10) at the apical foramen minus 1 mm. Chemo-mechanical preparation using continuous tapered NiTi-instruments (F6 SkyTaper, Komet, Lemgo, Germany) was performed after establishing a manual glide path. NaOCl (3%) served as irrigation solution in combination with sonic activation at 6000 Hz (EDDY, VDW, Munich, Germany) during preparation. Root canals were enlarged under copious irrigation between preparation cycles and instrument changes. Apical preparation size was based on a gauging procedure, but minimum size was 35/.06. After final irrigation protocol

(including EDTA for smear layer removal) canals were dried with paper points and obturated using warm vertical compaction (Schilder-technique) and AH Plus (Dentsply Maileffer, Baillagues, Switzerland) as sealer. Finally, root canal orifices were sealed with a composite material. Storage at 100% humidity at 37°C for 48 h to guarantee a complete setting of the sealer after obturation preceded the further investigations steps.

MRI and 3D reconstruction

One day before MRI examination, the teeth and a gutta-percha cone (Mtwo 25/.07, VDW, Munich, Germany) were embedded in 1% agarose in a 5 ml falcon tube and stored at 4°C overnight.

MRI was performed on a 9.4 T Bruker Biospec 94/20 (Bruker BioSpin GmbH, Ettlingen, Germany) equipped with a 35 mm quadrature birdcage coil (Rapid Biomedical, Rimpfing, Germany). The falcon tube with the embedded tooth or gutta-percha cone was placed on a customized positioning bed and fixated to avoid motion artifacts. 3D UTE sequence was used with the following parameters: time to repetition, 8.0 ms; time to echo, 0.020 ms; flip angle, 5°; averages, 4; scan time, 1 h 12 min; number of projections, 134526; polar undersampling, 1.52; Matrix, 256. Due to different types of examined teeth (maxillary molar, two mandibular molars and a mandibular premolar) field of view and spatial resolution had to be adjusted for each tooth ranging from $17 \times 30 \times 17 \text{ mm}^3$ to $17 \times 40 \times 17 \text{ mm}^3$ for field of view and from $66 \times 117 \times 66 \mu\text{m}^3$ to $66 \times 156 \times 66 \mu\text{m}^3$ for spatial resolution.

3D reconstruction of MRI datasets was performed with AMIRA software (Visage Imaging GmbH, Berlin, Germany). Briefly, the tooth components (dentin, pulp) or root canal treatment materials were encircled according to their different intensities in the slices and manually marked with the so-called Magic-Wand tool.

Further, MRI data were analyzed using profile plot analysis tool of ImageJ software (Version 1.50b, Wayne Rasband, National Institute of Health, Bethesda (Maryland), USA). Signal intensities are reported as arbitrary units (au) and values are given as mean $\pm$ standard deviation (SD). Measurements were made on each tooth and the gutta-percha cone in three exemplary sectional images at three locations.

No separate analysis of artefacts was carried out. The focus was on the evaluability of the images. The examiner was aware of the inherent artefact susceptibility of the MRI technology.

X-ray

Radiography was performed periapical on Soredex MINRAY (Soredex Oy, Tuusula, Finland): 70kV, 0,12 s using a VistaScan Mini View scanner (Dürr Dental SE, Bietigheim-Bissingen, Germany). The tooth was placed on an imaging plate of $3 \times 4 \text{ cm}$ (VistaScan Plus, Dürr Dental SE, Bietigheim-Bissingen, Germany).

X-rays were examined using a 30"-monitor with a resolution of 2560×1600 pixels (Dell 3008WFP, Dell Inc., Round Rock, TX) with the C-Web-Viewer (Centricity Enterprise Web V 3.0 (8.0.1400.188); GE Healthcare, Barrington, IL) in a darkened room. The examiner, presenting with board-certified skills in dental X-ray, evaluated the visibility of the radiographs concerning the dental structures and the distinguishability of the different materials used.

Cone-beam-CT

Cone-beam CT was performed on a KaVo 3D exam (KaVo Dental GmbH, Biberach/Riß, Germany) with the following parameters: type: landscape, 120kV, 5mA, slice thickness: 0,125mm, slices: 250, data collection diameter: 30mm, time: 7s. All samples were positioned on a plastic holder in water.

The CBCT-volumes were examined on a 30"-monitor with a resolution of 2560×1600 pixels (Dell 3008WFP, Dell Inc., Round Rock, TX) in a darkened room with the manufacturers software (KaVo eXam Vision, Version 1.9.3.13). Visibility of tooth structure and the distinguishability of the different materials used was investigated by an examiner with board-certified skills in dental CBCT imaging.

Histological sections

After preparation the teeth were embedded in Technovit 9100 (Kulzer, Wehrheim, Germany) and horizontally sectioned in 1mm steps from the apex with a

0.1mm-low-speed saw (Leitz, Wetzlar, Germany) under water-cooling. To avoid any artifacts by dehydration the teeth were kept moist in purified filtered water throughout all following experimental procedures.

All slices were observed under a digital stereomicroscope (Expert DN, Müller Optronic, Erfurt, Germany) at 25x magnification and pictures were taken.

Results

The different examinations (native tooth (Figure 1I a-e), after preparation (Figure 1II a-e), after obturation (Figure 1III a-e)) are assigned to the examination methods (photography (Figure 1I–III a), periapical X-ray (Figure 1I–III b), CBCT (Figure 1I–III c) and MRI (Figure 1I–III d,e)). MRI enabled visualization of the tooth as well as the pulp and root canal anatomy before the treatment with high spatial resolution (Figure 1I–III d). The root canals were completely displayed, including the apical foramen. Dentin shows a signal intensity of 6479 ± 779 au. The cementum apposition area at the premolar showed an intensity of 8103 ± 867 au and was distinguishable by MRI. In axial images, the pulp of the native tooth shows a high intensity of 17183 ± 2655 au. Inside the pulp canal, structures with lower intensity appear, that can be considered as residuals of the sclerosed pulp soft tissue 6752 ± 1112 au. A three-dimensional reconstruction based on the 3D

Figure 1 Exemplary images of a lower molar: I = native tooth; II = after root canal preparation; III = after obturation; a = photography; b = periapical X-ray; c = cbct axial and sagittal, d = MRI axial and sagittal; e = 3D-MRI reconstruction

data set is possible, also enabling to calculate root canal volume (Figure 1I–III e).

The root canal system after preparation could be easily displayed because the agarose (21297 ± 1257 au) had entered the canal system represented by a homogenous high signal. 3D reconstruction based on the data set was made (Figure 1. I–III d,e). MRI examination of the stand-alone gutta-percha cone itself reveals a low signal intensity of 5400 ± 1231 au.

While the filling materials (sealer and gutta-percha) could not be differentiated with X-ray image or cone-beam-CT (Figure 1. I–III b,c), since both materials are

radiopaque, MRI showed distinguishable signal characteristics for each component of the treated teeth (Figure 2b,c,d). This can be confirmed by quantitative analysis of MRI signal intensities: dentin (6479 ± 779 au) and gutta-percha (59400 ± 1231 au) differ by a value of about 1100au, hence distinction may be difficult in some cases regarding the standard deviations. The difference in the intensity of the gutta-percha to agarose is approx. 1,6000au. Whereas the sealer produces a high intensity (17997 ± 2138 au) (Figure 2b,c,d; 3a), the difference to gutta-percha is about 1,2600au. Therefore, also profile plots reveal distinct peaks for each component,

Figure 2 a = MRI (axial) and histological section of the dentinal crack (yellow arrow); b_{1,2} = sagittal MRI analysis with graphical visualization of the intensities; c_{1,2} = coronal MRI analysis with graphical visualization of the intensities; d_{1,2} = axial MRI analysis with graphical visualization of the intensities; e = axial MRI and the corresponding histological section; b_{1,2}-d_{1,2}: light blue arrows = intensities of sealer; dark blue arrows = gutta-percha; green arrow = hypercementotic dentin

Figure 3 a,b = 3D-MRI reconstruction; c = histological section of the mesial root; d = axial slice of the mesial root; green arrows = sealer-associated signals

especially with regards to gutta-percha versus sealer (Figure 2b,c,d).

3D reconstruction of the data was performed for all obturated teeth. Within the 3D models, the materials can be distinctively distinguished (Figures 1e and 3a,b). Matching of the root canal volumes of the native, prepared and filled teeth was possible.

Next, MRI was validated by histologic sections. The detection of the sealer in the histological slides widely corresponds to the MR images, but sensitivity of MRI seems slightly reduced compared to histology. MRI enabled to detect small sealer amounts (Figures 1d,2e,3a-c). However, the small difference between the intensities of dentin and gutta-percha is challenging. Nevertheless, MRI visualized even a dentinal crack (Figure 2a).

Discussion

Many factors influence endodontic treatment outcome. In principle, each step in endodontic therapy may promote or minimize endodontic success rates. Independent of the system used, huge amounts of root canal surfaces were left unprepared and withstanding bacteria to chemo-mechanical procedures led to an increased risk for post-treatment apical periodontitis.¹⁶

An adequate obturation quality after a proper chemo-mechanical disinfection of the entire root canal system is one of the key points in achieving favorable results. Obturation aims are the prevention of the passage of oral fluids containing bacteria and their toxins to the apical periodontium through the root canal.¹⁷ Recently,

various techniques and instruments were evaluated to facilitate and improve endodontic treatment steps.¹⁸ Therefore, research is carried out *in vitro* on extracted human teeth or teeth of animal origin, whereby the visualization is generated by sectional images or by micro-CT or even nano-CT.^{12–14,19} Micro-CT is claimed to be a powerful non-destructive 3D analysis tool for visualizing endodontic treatment *in vitro*.^{19–21} *In vivo*, conventional radiography and cone-beam-CT are used.^{22,23}

First approaches towards practicable intraoral MR imaging using special teeth coils are available – hence, there is potential for *in vivo* application of UTE-MRI after coil and sequence optimization.^{24–28} While air-tissue interface artifacts are avoided by using UTE-MRI, signal artifacts from surrounding water-rich tissue remain an issue and could be minimized by using spiral sequences or the pointwise encoding time reduction with radial acquisition (PETRA) sequence.^{29,30} Other approaches described to this issue include the use of hydrogen-poor materials for the construction of coil, bed and support.²⁴ In addition, other promising approaches are available to obtain additional information by MRI examination of dense biological materials about discriminating bound from pore water based on their relaxation properties.³¹ The extent to which this possible approach for human bone can be transferred to human teeth should be clarified by further studies.³¹ Further, the currently long scan durations are a major challenge to be addressed. However, as shown by our results, MRI is well suited for *in vitro* (material) research.

Especially with regard to the changes of root canal anatomy in the z-direction (longitudinal axis of the tooth), Peters et al. (2000) postulated a resolution of at least 34 to 68 µm being sufficient for endodontic micro-CT studies,³² but resolutions < 10 µm are achievable.^{13,24} In the present study, a 66 µm resolution was achieved. Thus, values from current available literature for dental MRI were easily exceeded and demanded resolutions mentioned above were fulfilled.^{5,32} In order to obtain information of special details like sealer thickness, the presence of voids or lateral root canals, a higher resolution seems to be advantageous as different obturation techniques caused sealer film thicknesses between 2.2 and 47.6 µm.³³ Hence, further MRI studies may focus on improving spatial resolution. However, in this study MRI was capable to visualize the root canal anatomy accurately. In addition, differentiation between the used obturation materials was possible enabling to visualize even very thin structures (isthmuses, dentinal cracks, sealer), comparable to micro-CT analysis.³⁴ Visual differentiation of dentin versus gutta-percha was possible but remained challenging due to the similar signal in MRI. In further investigations, optimizing of UTE MRI sequence is needed or different obturation materials or additives (contrast agents) may be considered to enhance signaling.

The presented MRI technique is in principle suitable for research on endodontic treatment, the evaluation of all intermediate steps and the obturation. Compared to micro-CT examinations in this field, the resolution of the micro-CT examination seems to be even more accurate and presents higher resolutions.^{13,24} However, the special features of MRI technology may benefit especially the differentiation of the different obturation materials (e.g. sealer, voids).

The small number of specimens that have been investigated limits this preliminary study. Root canal preparation with NiTi instruments and a warm vertical obturation technique with widely used materials (gutta-percha; epoxy-resin-based sealer) were used. Thermo-plastic obturation techniques easily reach percentage values of gutta-percha and sealer in total of more than 90% of the complete root canal filling and even values above 99% were documented.³⁵ Hence, visibility and demarcation of the materials – especially the little sealer amounts – were limited, too. Statements about the behavior of other materials in MRI cannot be made. The image quality in this study was achieved under *in vitro* conditions and may hardly be achieved *in vivo* due to motion artifacts especially regarding the lower strength of magnetic fields currently used for human applications. Nevertheless, the MRI needs special experience in diagnosis to guarantee a proper interpretation of the images.

The promising results of this preliminary study should be proved in a larger sample size to assess artefact intensity and if the image methods are precise.

Conclusions

In summary, 9.4T UTE-MRI enabled to visualize root canal anatomy before and after endodontic treatment as well as the distinction of sealer and gutta-percha in a radiation-free, three-dimensional and non-invasive manner with a voxel size of 66 µm. Therefore, the technique may provide a versatile tool for research in endodontics.

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