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ORIGINAL ARTICLE

Three-dimensional localization of impacted teeth using magnetic resonance imaging

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Abstract Impacted teeth remain embedded in the jawbone beyond the normal eruption time with completed root growth. They can often get infected or damage neighboring teeth. Information about the three-dimensional position of impacted teeth is invaluable in orthodontic diagnosis and treatment planning. The purpose of this prospective study was to assess the feasibility of using magnetic resonance imaging (MRI) for the three-dimensional localization of impacted teeth in children and adults. The study included 39 patients from the pediatric age group with different tooth impactions and seven adults with impacted wisdom teeth. MRI yielded a clear separation between impacted teeth and the surrounding tissue, and the position and angulation of impacted teeth in all three spatial dimensions could be assessed. Compared to conventional radiography, dental MRI provides the advantage of full volumetric morphology accompanied by complete elimination of ionizing radiation, which is particularly relevant for repeated examinations of the pediatric group.

Keywords Magnetic resonance imaging · Dental MRI · Impacted teeth · Orthodontics

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Introduction

When tooth eruption has been mechanically impeded by the proximity of adjacent teeth, including supernumerary teeth, one speaks about *impaction* [1]. Impacted teeth remain under the gum and are not expected to erupt in a reasonable time. This occurs most commonly in the third molars with an average eruption age of 17–21 years and permanent maxillary canines with an average eruption age of 11–12 years [2]. Impacted teeth can get infected or damage neighboring teeth, often requiring surgical treatment. Exact three-dimensional localization of impacted teeth is invaluable in orthodontic diagnosis and treatment planning. However, this information is usually not available since only two-dimensional X-ray projections are routinely acquired [3–5]. Three-dimensional tuned-aperture computed tomography can sometimes improve assessment of impacted teeth but shows some limitations due to the small imaging area, especially in the case of horizontal impaction [6]. Dental computed tomography (dental CT) examination enables reliable three-dimensional localization of impacted teeth [3, 7]. However, the local radiation dose is high [8], which is particularly undesirable for young patients, and thus other techniques are being sought. Recently, cone beam CT (CBCT) devices, also called digital volume tomography scanners, have been introduced for dentomaxillofacial radiography [9]. Like conventional dental CT, this technique enables three-dimensional imaging but has the additional advantages of lower cost, smaller device size, and smaller radiation dose when compared to conventional CT [10]. CBCT has been evaluated for localization of impacted teeth [9, 11–15] and shows distinct advantages compared to the orthopantomographic images. However, the effective radiation dose of the CBCT, which varies significantly from one manufacturer to another, can still be between three and 44 times the typical dose of a panoramic radiograph [16]. Therefore, it must always be considered, especially when repeated examinations are required and the patient comes from the pediatric age group.

Magnetic resonance imaging (MRI) is an imaging modality widely used for medical diagnosis which does not use any ionizing radiation. In dentistry, MRI has been mostly used for imaging of the morphology and function of the temporomandibular joint [17–28], soft tissues, and tumors [29, 30] and for implant planning [31–38]. Studies of the inferior alveolar nerve have been performed using dental MRI (dMRI) with application of intravenous contrast medium [39–41]. Intravenous contrast agent administration has also been used to visualize dental pulp [42], to evaluate pulp vitality [43], and to assess reperfusion of autotransplanted teeth [44], as well as to demonstrate pulp cavity signal-intensity changes with age [45].

Although the signal from hard substances such as cortical bone and teeth is extremely low in medical MRI, it is possible to visualize them due to the high signal of adjacent soft tissues, fluids in the mouth, or bone marrow. Thus, MRI has been shown to enable accurate and reproducible three-dimensional measurement of the mandible due to the contrast between the cortical bone appearing black in MRI and the surrounding signal-giving soft tissue [46]. Visualization of two-dimensional tooth morphology has been possible due to the contrast between teeth appearing black and surrounding signal-giving bone marrow and soft tissues [42, 47]. The crowns of the teeth could be visualized due to the saliva retained in the subject mouth during scanning which played the role of contrast medium in the oral cavity [47]. Additional administration of gadolinium-based oral contrast medium enabled three-dimensional visualization of tooth crowns with a very high resolution [48–51] and measurement of caries lesions in vivo based on penetration of the contrast medium into the demineralized tooth substance [52].

The purpose of this prospective study was to assess the feasibility of MRI of three-dimensional localization of impacted teeth in children and adults, without application of an external contrast agent.

Subjects and methods

In accordance with the guidelines of the Ethics Committee of the Dental School of the University of Regensburg, dMRI was performed on 39 patients from the pediatric age group (mean age 12.4; range 8–18) with different tooth impactions, seven adults (mean age 26.7; range 21–32) with indications of impacted wisdom teeth, and 13 healthy volunteers (mean age 28.1; range 20–53). The total number of impacted teeth in the pediatric group was 52. The most frequent impaction type in the pediatric group was impacted permanent maxillary canines (19 canines, 37% of all impacted teeth). All examinations were performed with informed consent of the patient's legal guardian or themselves, depending on age.

Three-dimensional images were acquired using a 1.5-T MRI scanner Magnetom Avanto (Siemens Medical Solutions, Erlangen, Germany) in combination with a four-channel multifunctional radio frequency (RF) coil array (Noras MRI Products GmbH, Höchberg, Germany). The measurement setup is shown in Fig. 1. Imaging parameters were optimized in order to acquire a high-resolution 3D data set with a high contrast-to-noise ratio between teeth and surrounding tissues, in measurement times that could be tolerated by pediatric patients. A 3D Turbo Spin Echo sequence with TR/TE=1,000/10 ms and turbo factor 17 was employed. The average field of view (FOV) was $10\times 6\times 5$ cm^3; the average resolution was $0.78\times 0.78\times 1$ mm^3. The measurement time was 4 to 5 min.

In order to compensate for the nonuniform sensitivity distribution of the array of surface coils, automatic and manual signal-intensity normalization techniques were applied. Automatic normalization based on a body coil prescan was accomplished using the software package on a

Fig. 1 Measurement setup: four-channel multifunctional RF coil array is fixed in contact with the mouth of the patient

workstation (Siemens Medical Solutions, Erlangen, Germany). Manual normalization was performed by acquiring an identical three-dimensional data set using a perfectly uniform phantom and by consequently scaling the signal intensity of the data set acquired in vivo using the MATLAB programming environment (MathWorks, Natick, MA, USA).

For the evaluation of the results, three different visualization techniques were used: standard cross-sectional views from the three-dimensional data sets, panoramic curved cut view, and three-dimensional rendering of separately segmented teeth. Panoramic curved cut view could be obtained using the software package on the workstation, whereas three-dimensional rendering was performed using Amira software (ZIB, Berlin, Germany) after interpolation and semiautomatic segmentation using a region-growing algorithm.

Results

Measurement times of 4 to 5 min were well-tolerated by both adult and pediatric age groups. Reexamination had to be performed in three cases: in two cases due to the motion of the patient and in the third case due to the patient's open mouth during scanning. Localization of impacted maxillary canines was not possible in one patient because of a strong image artifact caused by metallic orthodontic braces. In all other patients, MRI yielded a clear separation between impacted teeth and the surrounding tissue, and the position and angulation of impacted teeth in all three spatial dimensions could be assessed. Thus, 51 impacted teeth were imaged in the pediatric group, including 18 canines, 14 of which were palatal impactions and four buccal.

As an example, Figs. 2, 3, and 4 demonstrate a case of an impacted permanent maxillary canine. A panoramic radiograph is shown in Fig. 2. Three cross-sectional views from a three-dimensional MRI data set and a panoramic view (curved cut through the MRI data set) are shown in Fig. 3. The result of the data segmentation and 3D rendering is shown in Fig. 4. Thanks to the contrast between the teeth and surrounding tissue (gums, tongue, cheek, saliva, and bone marrow), the surface of every tooth could be reconstructed separately using semiautomatic segmentation. Three-dimensional rendering of the dentition of another patient who underwent dMRI is shown in Fig. 5, demonstrating an impacted third molar. One case of root resorption of the maxillary lateral incisors that could not be detected using a panoramic radiograph (Fig. 6) but could be well-visualized using dMRI is shown in Fig. 7.

All three dMRI visualization techniques (three cross-sectional views, panoramic view, and three-dimensional rendering) allowed for assessment of the position and angulation of impacted teeth. Automatic normalization of the image intensity improved intensity distribution but did not work perfectly and subsequent segmentation was done with different threshold values. Manual normalization showed much better results but was time consuming and not suitable for routine application. The threshold value for separation of the teeth from the surrounding medium was always set at half of the average signal-intensity value of the surrounding medium.

Fig. 2 Panoramic radiograph showing an impacted permanent maxillary canine

Discussion

Three-dimensionality and the absence of ionizing radiation make dMRI a flexible and safe tool for orthodontic and surgical treatment planning. The results of this paper demonstrate that dMRI is well suited to three-dimensional localization of impacted teeth in children and adults. No external contrast agent is needed due to the natural contrast between teeth, which are invisible in clinical MRI, and surrounding signal-giving tissue, such as bone marrow in maxilla and mandible, gums, tongue, cheeks, and saliva present in the oral cavity.

Difficulties with achieving a signal contrast can take place at teeth/air transitions which cannot be distinguished in dMRI. This is the case when the mouth of the patient is open or when the tooth roots reach the maxillary sinuses. Additionally, almost no contrast is achieved at the transitions between the teeth and the cortical bone. The periodontal ligament space was too thin to be detected in MRI images with a resolution slightly below 1 mm. In the case of 3D segmentation, this fact necessitated manual separation of the teeth from the cortical bone, causing unevenness on the rendered tooth surface (Fig. 5).

Apart from 3D localization of teeth, dMRI shows potential to provide other valuable diagnostic information, such as information about root resorption. Due to overlap of anatomic structures on conventional radiographs, diagnosis

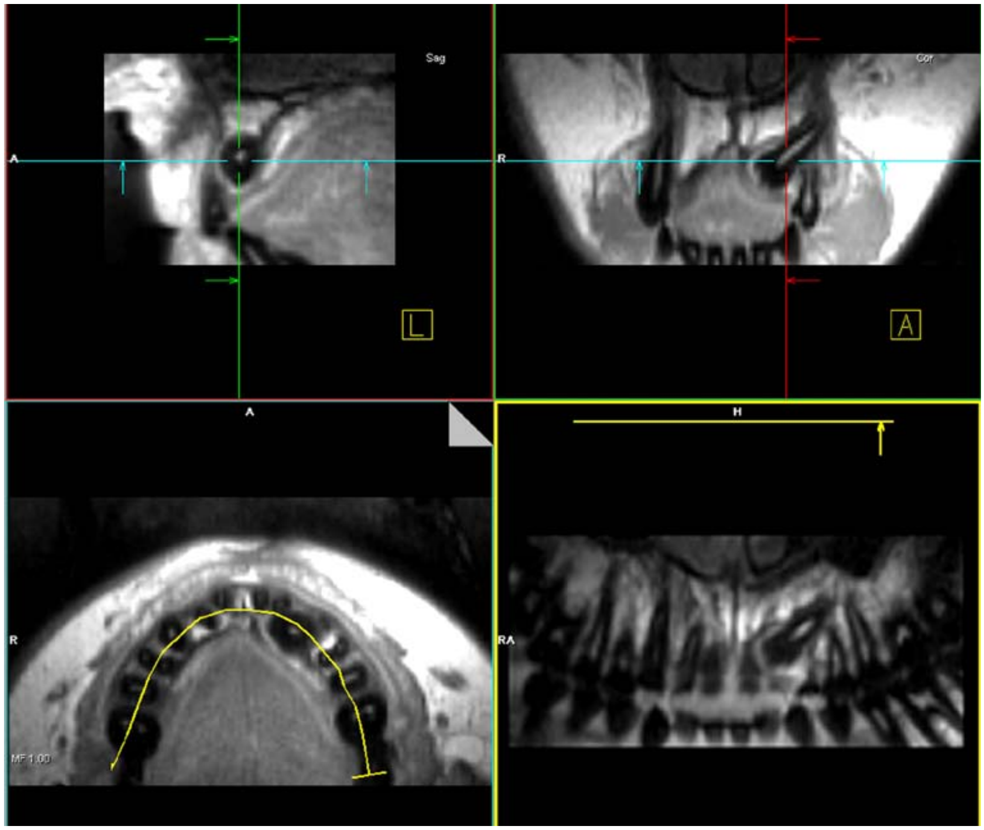

Fig. 3 Three cross-sectional views from a 3D MRI data set and a panoramic curved cut view

of root resorption is often complicated, which leads to false-negative results in about 51.9% of the cases [53].

Various dental materials present in the subject's mouth present a major concern for dental applications of MRI. In the presented study, localization of impacted maxillary canines was not possible in one patient because of a strong image artifact caused by metallic orthodontic braces. Although well-fixed wires pose no risk to the patient in the magnetic field of a clinical MRI scanner [54], the artifacts caused by it can make the acquired images useless. In some cases of the presented study, composite fillings caused local image distortion, which can be seen on the 3D rendering of the tooth (Figs. 8 and 9). A probable reason for the strong distortion is the presence of metal oxides such as iron oxide in some dental composite fillings and, as a consequence, significant difference between the magnetic susceptibility of the composite material and that of the surrounding tissue [55]. However, these distortions did not affect localization of the impacted teeth. Partly contradictory results have been reported regarding the severity of image artifacts caused by different dental materials [56–61]. The conclusion about whether materials cause strong

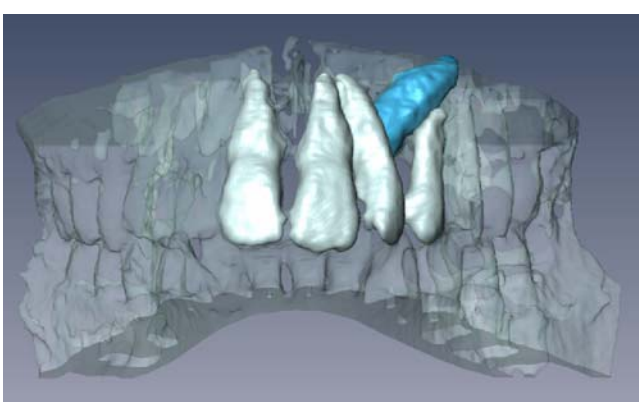

Fig. 4 3D rendering of the segmented MRI data set

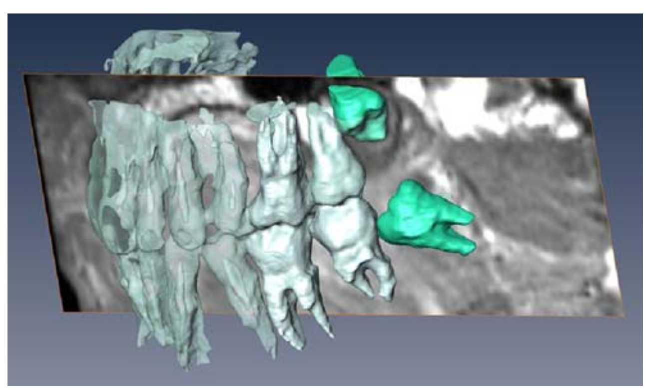

Fig. 5 3D rendering of the segmented MRI data set showing an impacted third molar

Fig. 6 Panoramic radiograph showing impacted permanent maxillary canines

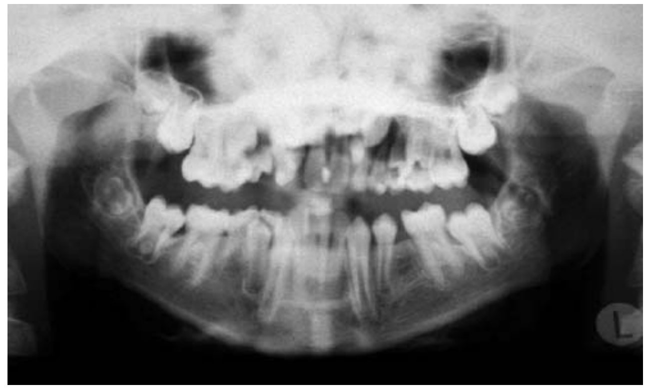

Fig. 8 Panoramic radiograph with a visible filling material in the maxillary central incisors

artifacts, moderate artifacts, or no effect depends on many factors such as magnetic field strength, pulse sequence, image resolution, and the related gradient field strength, imaging plane, amount and shape of the dental material, distance between the object of interest and the material, etc. In other words, it is primarily the application that determines the degree of severity of the artifacts associated with different dental materials. In the case of localization of impacted teeth using dMRI, major problems are expected in the case of fixed metallic orthodontic appliances and metallic dental implants, the latter however being rarely encountered in pediatric patients.

All of the three assessed dMRI visualization techniques (three cross-sectional views, panoramic curved cut view, and three-dimensional rendering) allowed the assessment of the position and angulation of impacted teeth. The cross-sectional views and panoramic view with a moving curved cut were easily accessible at the scanner console directly after the measurement and could therefore be well suited for routine diagnosis. Since maxillary and mandibular teeth do not lie in one panoramic plane, double cut at different angles could improve panoramic visualization [62]. In the presented study, the three-dimensional surface rendering was performed separately using Amira software. Although this visualization technique provides the best understanding of the three-dimensional situation, in the present form, it is too time consuming for routine diagnosis.

Indications of use of dMRI and 3D imaging in orthodontics generally include unclear spatial position of impacted teeth, overlap of dental structures, and possible root resorption. Unique to dMRI is that it allows repetitive examinations to be undertaken in any age group without the need for consideration of radiation exposure. Contraindications for dMRI are the same as for any MRI examination and include cardiac pacemakers, implanted cardiac defibrillators, aneurysm clips, neurostimulators, metallic foreign bodies in the eyes, etc.

The aim of this publication was not to compare different imaging modalities in orthodontic diagnosis. However, a short discussion about the relative merits of dMRI compared to CBCT, the other imaging modality having a high potential in 3D diagnosis in orthodontics, might be

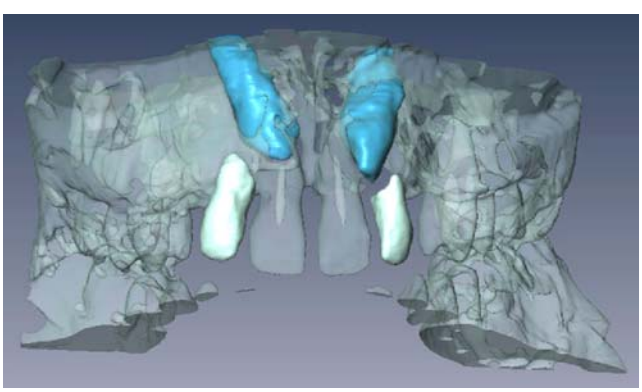

Fig. 7 3D rendering of the segmented MRI data set showing root resorption of the maxillary lateral incisors

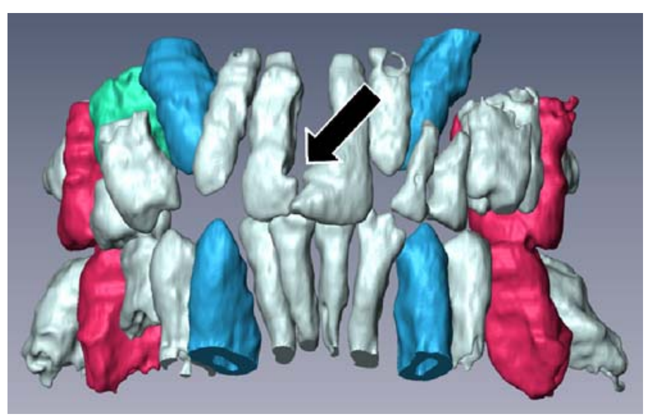

Fig. 9 3D rendering of the segmented MRI data set showing distortion of the surface of the maxillary central incisors caused by the filling material

interesting. The following short discussion considers the economic aspect and the technical properties of the two modalities. In order to consider economic merits, the prices of a CBCT and dMRI examination in the clinic of the University of Wuerzburg, Germany, were compared. As of February 2009, a CBCT examination of the dentomaxillofacial region costs 175€. Since there were no routine dMRI examinations or any other MRI examinations taking about 5 min being performed, the price for a 15-min examination of a joint was taken, which was 206€. The cost of a shorter MRI examination would be similarly lower. Prices for CBCT and MRI examinations can vary enormously in different clinics and even more in different countries. The given example was merely intended to show the same order of magnitude of the costs for the two modalities.

On the technical side, the quality of the obtained images is of interest. MRI appears to be inferior to CBCT in terms of spatial resolution. In the case of CBCT, spatial resolution of a data set with a FOV of 102 mm can be as small as 0.2 mm^3 [9]. However, the results presented in this paper demonstrate that interpolated dMRI data sets with an initial voxel size of slightly below 1 mm^3 provide the necessary information for localization of dental structures such as impacted teeth. Spatial resolution is not the only important merit of the image quality. The contrast-to-noise ratio, which is defined as the relationship of signal-intensity differences between two regions, scaled to image noise, is another technical characteristic important for distinguishing between two clinical areas of interest and decisive in the feature extraction process. This characteristic of images acquired with CBCT and dMRI needs to be compared in the future. There is room for improvement of dMRI image quality without increasing examination time or for reduction of the examination time without loss of image quality, which can be achieved on the RF hardware side or methodological side. A dedicated RF receiver coil array providing a better anatomic fitting and showing a high sensitivity in the whole region of interest—including wisdom teeth and the roots of the maxillary canines—would improve performance of dMRI. On the methodological side, an additional improvement can, for example, be achieved by applying parallel imaging methods such as SENSE [63] or generalized autocalibrating partially parallel acquisitions [64].

Metal artifacts affect both imaging modalities, albeit for different physical reasons. In CBCT, streak artifacts can be caused by an insufficient dynamic range of the X-ray detector for detecting the weak signal passed through metal objects or by beam hardening effects due to the nonlinear attenuation of the X-ray spectrum. In MRI, the reasons for metal artifacts are distortion of the applied RF field due to eddy currents in metals or, more commonly, distortion of the static magnetic field due to the difference in magnetic susceptibilities of metals and body tissues. Solutions to reduce metal artifacts are being sought in both MRI [65] and CBCT [66].

As mentioned before, dMRI is an attractive alternative to CBCT due to the complete absence of ionizing radiation. Another advantage that might become very important in the future is the sensitivity of MRI to abnormalities of soft tissues. This feature may drive development of MRI applications in other fields of dentistry, e.g., diagnosis of oral cancer, and consequently make MRI more accessible for orthodontic purposes too.

Conclusion

Dental MRI is a safe and well-tolerated imaging method which can be used for three-dimensional localization of impacted teeth in both adults and children. Three-dimensional data sets covering the whole area of interest with an isotropic resolution below 1 mm could be acquired in less than 5 min. Without administration of any external contrast medium, the position and angulation of impacted teeth in all three spatial dimensions could be assessed due to the contrast between the teeth and surrounding tissue, such as gums, tongue, cheek, saliva, and marrow of the jawbones.

Compared to the conventional X-ray-based diagnosis of impacted teeth, dMRI provides the advantage of full volumetric morphology accompanied by complete elimination of ionizing radiation, which is particularly relevant for repeated examinations of the pediatric group.

Conflict of interest The authors declare that they have no conflict of interest.

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