RESEARCH ARTICLE

High isotropic resolution magnetic resonance imaging of the mandibular canal at 1.5 T: a comparison of gradient and spin echo sequences

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Objectives: The precision of localizing the mandibular canal prior to surgical intervention depends on the achievable resolution, whereas identification of the nerve depends on the image contrast. In our study, we developed new protocols based on gradient and spin echo sequences. The results from both sequences were quantitatively compared for their agreement to identify the most suitable approach.

Methods: By limiting the field of view to one side of the mandible, three-dimensional acquisitions with T_1 weighted gradient and spin echo sequences were performed with $0.5 \times 0.5 \times 0.5 \text{ mm}^3$ resolution within 6.5 min covering the mandibular canal from the mandibular to the mental foramen. Aliasing artefacts were suppressed by different techniques. A manual segmentation of the mandibular canal from seven healthy volunteers was performed on this section by three different observers. The surface distance of the segmented volumes was computed between both sequences as well as between the different observers as a measure of equality.

Results: The quantitative comparison of the segmentation resulted in an average surface distance of $0.26 \pm 0.05 \text{ mm}$ between both sequences and an interobserver difference of $0.26 \pm 0.08 \text{ mm}$ for gradient and $0.29 \pm 0.07 \text{ mm}$ for spin echo data. By repeated evaluation, a difference of $0.15 \pm 0.02 \text{ mm}$ for gradient and $0.18 \pm 0.03 \text{ mm}$ for spin echo data was observed, indicating a slightly higher variability for spin echo images.

Conclusions: Both sequences can be used to achieve high-resolution images with good contrast and can be used for precise localization of the mandibular canal. Despite a slightly increased difference for the spin echo data, the advantage of an easy and robust setup remains.

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Introduction

Recent studies have already demonstrated the possible application of MRI for various fields in dental medicine

such as diagnostics^{1–4} as well as creating data sets for dental impression.⁵ Additionally, several comparisons with X-ray-based methods such as CBCT have shown good agreement between MRI and CBCT.^{6,7} One focus for the application of MRI in dental imaging was the localization of the mandibular nerve^{7–10} for diagnostic or pre-surgical evaluation of the nerve's course relative

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to dental roots. Although CBCT allows acquiring three-dimensional (3D) high-resolution images (typically 0.4 mm resolution¹¹), the contrast between the nerve and its surrounding tissue (*i.e.* bone marrow) is inherently weak. This is a direct consequence of CT's sensitivity to different radiation absorption rates, which is almost the same for different types of soft tissue.

In contrast to that MRI provides a better soft-tissue differentiation, since it is sensitive to the nuclei and the chemical constitution in their surroundings. Eggers *et al*⁷ evaluated the ability of different MRI sequences at 1.5 T field strength for the depiction of the mandibular canal and rated a 3D gradient echo protocol [volumetric interpolated breathhold examination (VIBE)] to perform best. Different publications have already proven the accuracy of VIBE MRI in comparison with CT images.^{7,8,12} Although the image resolution is lower than in CT images and an anisotropic voxel size is used, the identification of the canal was found to be easier due to its higher soft-tissue contrast. In addition to the 3D gradient echo, a two-dimensional *T*₁ weighted turbo spin echo (TSE) provided good tissue contrast and differentiation.⁷ Nevertheless, anatomical features were poorly resolved due to the large slice thickness as a consequence of two-dimensional multislice imaging.

Since the equivalence of gradient echo MRI and CBCT has been shown already, we are focusing on improving MR images and compare the results of gradient echo (VIBE) and spin echo sequences (TSE). A fair comparison of both sequences requires a 3D protocol at the same spatial resolution for gradient and spin echo and approximately identical scan times. However, scanning a large field of view (FoV), such as the whole mandible, at high resolution requires long scan times. This affects especially the TSE protocol, where only few readouts per unit time compared with a gradient echo sequence are acquired. Therefore, several modifications in the sequence protocols are necessary to achieve reasonable scan times. In the following, a new high-resolution MRI approach for the depiction of the mandibular morphology is shown for gradient and spin echo imaging. To increase slice resolution for a *T*₁ weighted TSE image of the mandibular nerve, a 3D protocol has to be used. The accuracy and reproducibility of locating the nerve canal is compared with a 3D VIBE and a 3D TSE protocol at the same isotropic spatial resolution by different observers.

Methods and materials

MRI

Typical MR protocols currently used for visualization of the mandibular canal use an anisotropic resolution of 0.8 × 0.8 × 1 mm³ voxel size. Based on the widely used VIBE parameters, several optimization steps were used to improve resolution and achieve an isotropic size of 0.5 × 0.5 × 0.5 mm³.

First, the FoV was limited to the region of interest, *i.e.* one side of the mandible. This allows for higher

resolution at constant scan time. To avoid aliasing artefacts in the phase-encoding direction (foot–head), the signal originating from outside the FoV has to be suppressed. In the case of VIBE, this was achieved by placing regional saturation bands at the edges of the FoV in the phase-encoding direction. Although the same technique could be used in TSE too, we decided to limit the FoV in the phase-encoding direction by using the reduced FoV (rFoV) technique.¹³ Instead of applying the refocusing pulses on the slice axis, they are played out on the phase-encoding axis. Thus, only the spins within the intersection volume of slice selection and refocusing pulses are effectively refocused. To assure refocusing of all spins within the desired volume of interest, the slice thickness of the refocusing pulse has to be adjusted to the dimension of the FoV in the phase-encoding direction, thereby aliasing artefacts that might occur in the phase-encoding direction are suppressed. Thus, the FoV can be freely reduced to the region of interest. This method allows an easy setup for imaging the desired small volume, since no saturation bands have to be aligned. Furthermore, the specific absorption rate is reduced by the lack of additional saturation pulses.

The relevant scan parameters have been provided in Table 1. For TSE imaging, a turbo factor of eight was used. Asymmetric echo was activated for VIBE imaging without partial Fourier in any of the phase-encoding directions. Echo time for VIBE imaging was set to match the opposed phase condition to highlight the transition between nerve and the surrounding tissue and to meet a similar depiction of the nerve as in the study of Eggers *et al*,⁷ which has already been proven to match well with CT data. The total scan time was identical for both sequences for better comparison of signal efficiency.

Second, instead of a commonly used head coil, two commercially available four-channel multifunctional coils (Noras, Höchberg, Germany) were placed close to the mandible (one four-channel coil on each side; Figure 1). Both coils are mounted on a flexible holder to place them properly. This setup serves additionally as a fixture of the head to avoid motion artefacts by undesired rotation of the head during the measurements. Although the presented protocol would require only one coil on one side of the head, the second one was used for fixation and further measurements, since the combination of both coils covers the entire dentition.

Table 1 Scan parameters for volumetric interpolated breathhold examination (VIBE) and turbo spin echo (TSE) protocol

Scan parameters	VIBE	TSE
Repetition time	9 ms	500 ms
Echo time	2.7 ms	9.7 ms
FoV (mm)	128 × 76 × 44	128 × 72 × 22
Matrix size	256 × 152 × 88	256 × 144 × 44
BW/px (Hz)	190	200
Acquired resolution	0.5 × 0.5 × 0.5 mm ³	
Scan time	6.5 min	

BW/px, bandwidth per pixel; FoV, field of view.

Figure 1 Examination setup for the MRI studies. The two four-channel receiver coils are positioned closely to the subject's mandible.

Furthermore, this provides the possibility to measure the opposite side using the same technique too.

Cohort

As an initial study, seven healthy, informed and consenting volunteers underwent MRI examination on a clinical 1.5 T scanner (Siemens Healthcare, Erlangen, Germany) with the described setup and protocol. Only volunteers without any dental implants or defects were included in the study. Both sides of the dentition were scanned,

resulting in a total of 14 available anatomical data sets for each sequence. One data set had to be discarded due to poor image quality, as a consequence of motion artefacts, leaving 13 different anatomical data sets for evaluation.

Data analysis

To perform a quantitative SNR comparison of both sequences, separate noise scans with fixed bandwidth per pixel were included in the protocol. This allowed reconstruction of images in SNR units.¹⁴ The noise level has been scaled by the different bandwidth values of the sequences. A central slice, such as is shown in Figure 2a,d, was chosen for a representative evaluation. SNR was evaluated in, as far as possible, homogeneous signal regions of the mandible (bone marrow) and mandibular canal. The common method by selecting separate noise and signal regions in the images was difficult to apply in this study due to the almost completely filled FoV containing hardly any region with pure noise.

To compare the accuracy of locating the mandibular canal, a segmentation of the canal was performed. Images were resampled in Amira® (FEI, Hillsboro, OR) to an isotropic voxel size of 0.25 mm using a Mitchell filter. Three experienced Amira users (named A, B and C) were asked to manually segment the mandibular canal in both TSE and VIBE data sets. Segmentation of the canal started at the mental foramen and followed the nerve's course to the mandibular foramen to assure that the same volume was analyzed by all persons.

Figure 2 Representative orthogonal slices from turbo spin echo (TSE) (a–c) and volumetric interpolated breathhold examination (VIBE) (d–f) data. The approximate positioning of the slices (b, c, e, f) is indicated by the dashed lines (a, d). The mental foramen can be clearly seen in (c) and (f).

Segmentation was carried out in sagittal slices (Figure 2a,d) for efficient processing. The selected volume was then smoothed using a $3 \times 3 \times 3$ kernel to remove most of the irregularities caused by the slice-by-slice segmentation. Based on the selected volume, a 3D surface model was computed without further smoothing to preserve small structures. A two-sided surface distance between TSE and VIBE surface was calculated, and the mean surface distance was considered as a measure of equality to assess intersequence agreement. To avoid errors arising from unwanted motion between the scans, both surfaces were aligned using a rigid transform prior to calculation of surface distance. Alignment was performed automatically by iterative rigid transforms to minimize the distance between both surfaces.

Interobserver agreement was analyzed by calculating surface distance between the same data sets from different observers for TSE as well as VIBE data. In this case, no surface alignment was applied. Additionally, one observer repeated the segmentation (named A1 and A2) after several weeks to assess the intraobserver reproducibility.

Since surface distance does not distinguish which surface is inside or outside, the volumes for TSE and VIBE data were calculated to determine, if there is a general over- or underestimation of the thickness. The volumes obtained from each observer were tested for significant differences between the sequences using the Student's *t*-test with a significance level of 0.05 after normal distribution of the data had been proven by the Kolmogorov–Smirnov test.

Results

MRI

Orthogonal images in sagittal and frontal orientation from both protocols are shown in Figure 2. The isotropic voxel size allows retrospectively choosing different slice orientations without losing image quality. Sagittal, frontal and other oblique orientations can be chosen while having the same in-plane resolution.

The efficacy of the reduced FoV technique can be seen in Figure 2. Although there are small aliasing artefacts visible in the upper parts of the image, no relevant anatomical detail is superimposed. Comparing it to the efficacy of the regional saturation bands, which were used for VIBE imaging, the result in suppressing aliasing artefacts is almost identical.

SNR evaluation resulted in an average SNR of 55 in the bone marrow of the mandible and 22 in the nerve canal for TSE. The VIBE image had an SNR of 31 in the bone marrow and 18 in the nerve canal.

The nerve's course can be followed along the entire mandible, as can be seen in the sagittal plane. Location of landmarks such as the mental foramen is easily feasible in both sequences (Figure 2c,f). The achieved high

Figure 3 Surface rendering of the nerve canal and mandible with teeth based on turbo spin echo images.

resolution allows identifying even small details such as the nerve branches running to the roots of the teeth. The covered volume is visualized by a 3D surface rendering of the data (Figure 3). Based on a manual segmentation of the TSE data shown in Figure 2a–c, all relevant structures (*e.g.* teeth, roots and bone) can be localized.

Segmentation comparison

An exemplary comparison of the segmented nerve canal in both, TSE and VIBE images, can be seen in Figure 4. The combined surface view of TSE (green) and VIBE data (purple) shows large areas of purple. This indicates a larger volume for the VIBE data, since the segmented canal from TSE data is covered inside.

Looking at the local surface distance of both canals (Figure 5), large areas of blue indicate a good agreement of both segmentations. Larger deviations appear only around the mental and mandibular foramen. The average distance of both surfaces in this case is 0.20 mm.

The mean intersequence surface distance from all observers (A1, B and C) was 0.26 ± 0.05 mm (Figure 6). The single values range from a minimum of 0.19 mm to a maximum of 0.40 mm. Almost identical surface distances were found by each observer. The results were reproducible by the same observer with a mean surface distance of 0.25 ± 0.04 mm in the first evaluation (A1) and 0.24 ± 0.04 mm in the second (A2).

Figure 4 Combined nerve canal surface based on turbo spin echo (TSE) (green) and volumetric interpolated breathhold examination (VIBE) (purple) with VIBE image in the background.

Figure 5 Surface reconstruction of the nerve canal based on turbo spin echo (a) and volumetric interpolated breathhold examination (VIBE) (b) image data superimposed on a respective slice. The colour indicates the local distance to the other surface.

Overall, interobserver comparison resulted in a mean surface distance of 0.26 ± 0.08 mm (Figure 7), with values ranging from 0.15 to 0.42 mm for the VIBE images. Based on the TSE images, the surfaces of the single observers differed on average 0.29 ± 0.07 mm, with 0.17 mm as minimum and 0.57 mm as maximum values. The repeated evaluation by the same observer resulted in a mean difference of 0.15 ± 0.02 mm for VIBE images and 0.18 ± 0.03 mm for TSE images. There is a statistical significant difference between the results for TSE and VIBE for Observers A1 and A2 and for Observers A1 and B.

The segmented volume of the canal in TSE and VIBE images resulted in larger values for VIBE images in three cases (approximately 10% difference), whereas only the results from Observer A were significantly different (Figure 8). The average volume from Observer C is almost identical in both sequences. However, there is a larger deviation in the results from the VIBE images for all observers.

Discussion

By optimizing the FoV to the anatomical region of interest, the total scan time can be reduced and data with high isotropic resolution can be acquired within reasonable scan time. The achievable voxel size is only slightly larger than from typical CBCT data (typically 0.4 mm isotropic resolution¹¹). Since contrast between the nerve canal and the surrounding tissue is higher for

MRI and no ionizing radiation is used, the method offers important advantages to conventional CBCT imaging.

The use of surface coils leads to an increased signal compared with a standard head coil, which allows achieving high spatial resolution. This is mainly an effect from the shorter distance between the coil elements and the mandible in case of our setup. Additionally, the head is effectively fixed by the two coils, as only one out of 14 data sets had to be discarded due to motion artefacts. Although fixation prevents rotation of the head during measurement, the mandible can still be slightly moved up and down. Therefore, there is still need for patient cooperation to avoid too large motion artefacts. As our volunteers were required to rest for four consecutive measurements (both sides with VIBE and TSE) in the scanner, the probability of motion artefacts in our group of volunteers is expected to be higher than in daily routine, when only one or two high-resolution measurements are necessary.

Although our protocol relies on unilateral imaging of the mandible, the setup can be used without any changes for imaging the opposite side, as we did in this study offering full-volume coverage of the mandible.

Image quality

Despite the fact that two completely different techniques for suppressing aliasing artefacts were used, the results are very identical with respect to suppressing aliasing artefacts. Therefore, the use of reduced FoV (rFoV) technique in spin echo sequences can be

Figure 6 The average surface distance from 13 canals of turbo spin echo vs volumetric interpolated breathhold examination (VIBE) for different observers.

Figure 7 Mean interobserver surface distance for volumetric interpolated breathhold examination (VIBE) and turbo spin echo (TSE) data. The TSE data show a general larger surface distance in all cases.

Figure 8 The average segmented volume of the canal in turbo spin echo (TSE) and volumetric interpolated breathhold examination (VIBE) images for different observers.

regarded as an equal alternative. Beside the same efficiency in suppressing aliasing artefacts, the rFoV technique offers some advantages. As no additional saturation bands have to be placed properly, the protocol setup is easy and fast. Furthermore, the absence of additional radiofrequency pulses for saturation in this TSE sequence also reduces the specific absorption rate, which is of interest when imaging is performed at higher field strengths.

Image quality of both sequences is very good and the high resolution allows visualization of small anatomical details. The course of the nerve canal can be followed from the mental foramen to the mandibular foramen without interruption. Thanks to the high and isotropic resolution, the canal can be located in any of the orthogonal views with the same accuracy. Even if a slightly different slice orientation is of interest afterwards, oblique reformatting of the volume can be performed with low loss of image quality.

Although both protocols provide mainly T_1 weighted contrast, the VIBE sequence is more sensitive to susceptibility differences due to its gradient echo nature. This is of interest, if dental implants are already present. Depending on the material, heavy artefacts can appear in gradient echo images, whereas they are minimized in spin echo images.^{15,16} In our case, the same effect results in an apparent increase of trabecular structure within the mandible as a consequence of the different susceptibilities of the bone and bone marrow. Additionally, the different precession frequencies of water and fat lead to signal cancellation at the chosen echo time (“opposed phase”). This leads to dark lines between different types of tissues improving the visual perception of separate objects. However, it also introduces some additional uncertainty with respect to the actual transition, which is hidden by the signal void, between the nerve and surrounding tissue. On the other hand, this could be solved by changing the echo time in VIBE imaging to miss the opposed phase condition. But in this case, the clear separation of nerve and surrounding bone marrow will be diminished. As spin echo sequences refocus all spins with different frequencies at the same time, this effect does not occur in TSE images. However, the varying echo time during the echo train adds a T_2

weighted filter to the data, leading to a slight blurring in the images.

Segmentation

To understand the influence of the different depiction of the anatomy on the accuracy, a closer look at the interobserver agreement is necessary. Although there is a better delineation of the nerve canal and the surrounding tissue in the VIBE images than in the TSE images, the quantitative analysis of the surface distance reveals only slightly different results in both sequences. Yet, there is a generally larger distance between the results from the TSE images for all observers than from VIBE images, indicating a larger variance in the manual segmentation of TSE data. This increase of average distance can be attributed to the different depiction of the nerve and a slight blurring in the images as previously mentioned. However, the average interobserver agreement for both sequences is about the same as the intersequence agreement for each observer. Thus, the variation caused by the different sequence is of the same order as the difference caused by the various observers. Therefore, it finally cannot be concluded that the major difference between the results is caused by the different depiction of the sequences or a different segmentation of the observers. However, small differences between results for TSE and VIBE in the interobserver agreement indicate a very similar depiction and accuracy for both sequences. Finally, it should be noted, that the average difference for both sequences is just about the order of the interpolated voxel size. Nevertheless, both sequences offer even higher accuracy, if the segmentation process is better regulated, as it is here in the repeated segmentation of A1 and A2 with reduced interobserver variability. Much smaller mean and deviation are observed for the comparison of A1 and A2 for both TSE and VIBE. Therefore, full or semi-automatic segmentation procedures are expected to minimize the differences by reducing the individual variation of an observer.

Conclusion

A new approach for imaging the mandibular canal using MRI has been demonstrated and a comparison of gradient and spin echo sequence variants was performed. The new approach allowed achieving high isotropic resolution images with high accuracy in localizing the mandibular canal. Only small differences between both sequences were observed, with a slightly larger variation for TSE data. However, the proposed TSE protocol allows an easy setup without aliasing artefacts and in apparently less noisy images. A reasonable scan time of only few minutes allow for a use in daily diagnostic to precisely locate small lesions or the mandibular canal. Compared with clinically used CBCT imaging MRI provides better contrast without the use of ionizing radiation. The presented protocols

bring MRI even closer to CBCT with respect to resolution, which makes it a promising alternative for daily diagnostic within reasonable scan time. This can be achieved by both TSE and VIBE, although TSE offers

an easier setup and higher robustness at the cost of small loss in accuracy. Further optimizations, such as partial Fourier or parallel imaging to reduce scan time and their influence on accuracy need to be analyzed.

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