RESEARCH ARTICLE

MR imaging of the temporomandibular joint: comparison between acquisitions at 7.0 T using dielectric pads and 3.0 T

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Objectives: To qualitatively and quantitatively compare MRI of the temporomandibular joint (TMJ) at 7.0 T using high-permittivity dielectric pads and 3.0 T using a clinical high-resolution protocol.

Methods: Institutional review board-approved study with written informed consent. 12 asymptomatic volunteers were imaged at 7.0 and 3.0 T using 32-channel head coils. High-permittivity dielectric pads consisting of barium titanate in deuterated suspension were used for imaging at 7.0 T. Imaging protocol consisted of oblique sagittal proton density weighted turbo spin echo sequences. For quantitative analysis, pixelwise signal-to-noise ratio maps of the TMJ were calculated. For qualitative analysis, images were evaluated by two independent readers using 5-point Likert scales. Quantitative and qualitative results were compared using *t*-tests and Wilcoxon signed-rank tests, respectively.

Results: TMJ imaging at 7.0 T using high-permittivity dielectric pads was feasible in all volunteers. Quantitative analysis showed similar signal-to-noise ratio for both field strengths (mean $\pm$ SD; 7.0 T, 13.02 ± 3.92 ; 3.0 T, 14.02 ± 3.41 ; two-sample *t*-tests, $p = 0.188$). At 7.0 T, qualitative analysis yielded better visibility of all anatomical subregions of the temporomandibular disc (anterior band, intermediate zone and posterior band) than 3.0 T (Wilcoxon signed-rank tests, $p < 0.05$, corrected for multiple comparisons).

Conclusions: MRI of the TMJ at 7.0 T using high-permittivity dielectric pads yields superior visibility of the temporomandibular disc compared with 3.0 T.

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Introduction

Over the past decades, MRI of the temporomandibular joint (TMJ) has emerged as the state of the art to assess

pathologies underlying temporomandibular disorders (TMDs),^{1,2} such as structural alterations or displacement of the temporomandibular disc.^{3,4} Currently MRI of the TMJ is performed mainly at 1.5 T or 3.0 T.^{5,6} However, MRI results are still falling short of showing a clear association with reported symptoms.⁷ Furthermore, the

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impact of potential imaging findings on treatment choice and clinical outcome is still controversial,⁷ suggesting that the depiction of the TMJ in clinical routine is still unsatisfactory and may benefit from further optimization.

One explanation for the mismatch between clinical presentation of patients suffering from TMDs and MRI findings might be the insufficient performance of current standard MRI hardware and/or imaging protocols to depict the clinically relevant, relatively small anatomical key structures of the TMJ, such as the different regions of the articular disc, in full detail. According to this theory, this would mean that the image resolution needs to be improved, however, at a preserved signal-to-noise ratio (SNR). To achieve this, optimized coil designs or higher static magnetic field strengths, such as 7.0 T, could be used.^{8–11} Since the obtainable SNR is intrinsically linked to the static magnetic field strength in a linear way, imaging the TMJ at 7.0 T should theoretically enable—compared with for example 3.0 T—a higher overall SNR where a portion of the signal increase might be *inter alia* utilized to enhance spatial resolution.^{12,13}

Given those theoretical considerations, a growing number of studies are investigating potential benefits of MRI of the musculoskeletal system and/or head and neck regions at 7.0 T compared with 3.0 T, which is considered as standard reference in most cases.¹⁴ Most of those studies reported superior performance of MRI at 7.0 T for the knee, wrist or inner ear.^{13–16} However, no study, so far, has assessed whether MRI of the TMJ at 7.0 T might indeed yield superior performance compared with 3.0 T when using optimized clinical sequences. The lack of studies in this area can be mainly explained by the fact that imaging the TMJ at 7.0 T is very challenging and limited by several TMJ-specific and general methodological reasons. First, specific receiver arrays for imaging the TMJ at 7 T are still not commercially available, which is of particular importance for comparison studies since the coil design has a crucial influence on the SNR and makes it necessary to use standard head coils. Second, strong local inhomogeneities in the transmit radiofrequency field (B1+) caused by the elliptical head shape and susceptibility difference between different tissue types are considerably limiting the SNR in the lateral areas of the head, also affecting the areas where the TMJs are located.^{15,17,18} In addition to those observations, several other general considerations are further complicating the realization of such studies. The intrinsic T_1 time of soft tissue increases with higher field strength, which typically has to be addressed by longer repetition times (TRs) and subsequently longer acquisition times, increasing the risk of movement artefacts.¹⁹ In addition, different tissue relaxation properties might result in different effects of the higher magnetic field strength on SNR.¹³ Furthermore, regarding SNR calculation, most of the commonly used algorithms do not account for the distinct spatial variations of noise levels, which are *inter*

alia introduced by multichannel imaging and provide therefore unreliable results, especially when comparing coils with a different number of receive channels.¹³

Recently, the feasibility of imaging the TMJ at 7.0 T has been demonstrated for the first time using a commercially available 32-channel head coil and special high-permittivity dielectric pads consisting of barium titanate.²⁰ The pads increased the local B1+ fields in the areas covering the TMJs,¹⁵ thus increasing the local SNR and facilitating imaging of the TMJ at 7.0 T. Furthermore, recent studies provided first proof that intricate algorithms calculating SNR on a voxel-wise basis and taking noise correlation among channels into account were applicable for imaging the TMJ and yielded robust results.^{13,20} Nevertheless, a systematic evaluation of this novel approach to image the TMJ at 7.0 T with respect to the current benchmark examination, which is high-resolution MRI at 3.0 T, was not performed.

Therefore, the aim of the current study was to quantitatively and qualitatively compare MRI of the TMJ at 7.0 T utilizing high-permittivity dielectric pads with high-resolution 3.0 T imaging.

Methods and materials

The local institutional review board (IRB) approved the current prospective MRI study in asymptomatic volunteers. This was a prospective IRB-approved MRI study. It included imaging of a phantom and a cohort of asymptomatic healthy volunteers. All volunteers gave written informed consent. The IRB approval did not allow inclusion of patients. Thus, only asymptomatic volunteers could be included. Written informed consent was obtained from all participants. The study was registered in the official research database of the University of Zurich, Switzerland.

Study subjects

12 healthy asymptomatic volunteers were included in the current study (6 females, mean age 25.7 years, range, 20–29 years and 6 males, mean age 26.5 years, range 24–32 years). Inclusion criterion was willingness to participate in this study. Exclusion criteria were current or past symptoms related to TMD, pregnancy, claustrophobia and metallic implants.

MRI

MR protocol: MRI was performed on a 3.0-T Philips Ingenia system (Philips Healthcare, Best, Netherlands) using a 32-channel head coil (SENSE head coil, 32 elements; Philips Healthcare) and on a 7.0-T Philips Achieva[®] system (Philips Healthcare, Cleveland, OH) using a quadrature transmit head coil in combination with a 32-channel receive array (NOVA Medical, Wilmington, DE) and special high-permittivity dielectric pads (see Dielectric pads section). Proton density

Table 1 Scan parameters of the proton density weighted (PDw) sequences in pseudosagittal orientation at 7.0 and 3.0 T, respectively

Parameter	PDw-TSE sagittal	
	7.0 T	3.0 T
FoV (mm)	150 × 150	150 × 150
Pixel size (mm)	0.4 × 0.4	0.5 × 0.5
Reconstructed pixel size (mm)	0.2 × 0.2	0.25 × 0.25
Slice thickness (mm)	2	2
Number of slices	2 × 12	2 × 12
TR	3300	2700
TE	22	26
wfs in pixel (mm)	1.52	1.199
Effective wfs in image (mm)	0.6	0.6
wfs (Hz)	674	362
TSE factor/ETL	7	7
ES	12	7.4
NSA/NEX	1	1
Scan time (min:s)	05:49	03:52

ES, echo spacing; ETL, echo train length; FoV, field of view; NEX, number of excitations; NSA, number of signal averages; TE, echo time; TR, repetition time; TSE, turbo spin echo; wfs, water-fat shift. The scan parameters are reported for each field strength.

weighted turbo spin echo sequences in oblique sagittal planes were acquired using the sequence parameters presented in Table 1. To ensure a correct angle, the planes were carefully oriented perpendicular to the transverse axis of the mandibular condyles according to recent studies performing clinical MRI of the TMJ.^{21,22}

Dielectric pads: For imaging the TMJ at 7.0 T, dielectric pads explicitly designed to improve the local B1+ field in the lateral areas of the head were used as described in a previous study.²⁰ Briefly, pads were manufactured using a suspension of barium titanate (325 mesh powder; Alfa Aesar GmbH & Co KG, Karlsruhe, Germany) and deuterated water (99.9%; Sigma-Aldrich, Zwijndrecht, Netherlands). The geometry of the manufactured pads was based on simulations performed by Brink *et al*¹⁵ and resulted in two different sets of dielectric pads for female and male volunteers due to gender-specific difference in head size and B1+ drop-outs (set for females: left side, 100 × 100 × 10 mm³; right side, 140 × 140 × 10 mm³; set for males: left side,

100 × 100 × 10 mm³; right side, 180 × 140 × 10 mm³; Figure 1).

Noise scans: For all volunteers, an identical scan without radiofrequency field (RF) excitation and gradient switching was performed subsequently to the aforementioned sequence at 7.0 T with dielectric pads and at 3.0 T without pads to measure noise and enable a voxelwise calculation of the SNR.

Volunteer imaging: All volunteers were scanned at 7.0 T using dielectric pads and at 3.0 T without dielectric pads. To avoid potential influence of the scan order on imaging results, volunteers were randomly assigned to the different magnetic field strengths with, in addition, half of the volunteers even scanned at different days (mean time between the scans 1.1 ± 1.22 days). For MRI at 7.0 T, the dielectric pads were placed centred on both TMJs of each subject. All images were taken with the mouth closed.

Data analysis

Signal-to-noise ratio measurements: Analysis of measured SNR followed the procedure previously described in full detail.²⁰ Briefly, SNR was evaluated on a voxelwise basis by post-processing the image data and corresponding measured noise for every coil channel using dedicated software routines (MATLAB[®]; MathWorks, Natick, MA), which resulted in voxel-based SNR maps. According to Nordmeyer-Massner *et al*¹³ and following a recently reported analysis algorithm,^{20–22} SNR was calculated as follows:

$$\text{SNR} = \frac{|\rho|}{\sigma}$$

ρ , maximal magnitude of the transverse magnetization within a voxel;²³ σ , standard deviation of the corresponding noise components.²⁴ Subsequently, each TMJ disc, fossa and condyle were manually segmented for each SNR map. Corresponding SNR values were extracted, resulting in one SNR value per tissue for each

Figure 1 High-permittivity dielectric pads. In this study, high-permittivity dielectric pads were used with properties extensively described in previous studies (for specific absorption rate and B1+ simulations, see Brink *et al*,¹⁵ and for detailed presentation of the particular application for imaging the temporomandibular joint, see Manoliu *et al*²⁰). (a) The set for female volunteers; (b) the set for male volunteers.

subject's TMJ. Calculation of theoretical SNR for turbo spin echo sequences was performed as follows:

$$\text{SNR} \propto \frac{B_0 \text{ Voxel size}}{\sqrt{\text{BW}}} \text{pd} e^{-\frac{\text{TE}}{T_2}} \left(1 - e^{-\frac{\text{TR}}{T_1}}\right) \sin \theta$$

where scanner parameters [flip angle (θ), static magnetic field (B_0)], tissue parameters (T_1 , T_2 , pd) and sequence parameters (voxel size, receiver bandwidth) are accounted for. The tissue parameter differences were taken into account by adapting the echo time (TE) and TR. The flip angle was optimized using the dielectric pads. For the remaining parameters, the clinically meaningful constrain of similar water–fat shift at the two field strengths was chosen. This implies a linear increase of the bandwidth relative to the static magnetic field as described by following formula:

$$\text{SNR} \propto \frac{B_0 \text{ Voxel size}}{\sqrt{\text{BW}}} \propto \sqrt{B_0} \text{ Voxel size}$$

Qualitative image evaluation: All images were anonymized (subject's initials blinded) and saved in the hospital's picture archiving and communication system (IMPAX® 6.0; Agfa Healthcare, Mortsels, Belgium). Subsequently, two fellowship-trained radiologists assessed independently all images (A.M. and F. DG. initials blinded) with respect to the overall image quality as well as to the visibility of the following clinically relevant structures: (i) articular disc (anterior band, intermediate zone and posterior band), (ii) bilaminar zone, (iii) mandibular fossa, (iv) mandibular condyle and (v) inferior lateral pterygoid muscle. The radiologists were blinded to the volunteers' details, field strength and the fact whether the 7.0-T or 3.0-T images were performed first. Images were shown to them randomly. The visibility of the aforementioned anatomical structures was graded on a 5-point Likert scale (1, excellent visibility and delineation; 5, complete lack of visibility).⁵

Statistical analyses: All statistical analyses were performed using SPSS® release 22.0 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL). Shapiro–Wilk tests were performed to test for normal distribution of the SNR. Paired sample *t*-tests were performed to assess differences between images acquired at 7.0 T and 3.0 T (significance level $\alpha = 0.05$) regarding SNR. Two-sample *t*-tests were used to evaluate potential differences in SNR between male and female volunteers at 7.0 T and 3.0 T (significance level $\alpha = 0.05$). To evaluate statistically significant differences between the images acquired at 7.0 T and 3.0 T with respect to the visibility of the anatomical structures of the TMJ as well as the overall image quality, Wilcoxon signed-rank tests were performed [significance level $\alpha = 0.05$, corrected for multiple comparisons ($n = 8$ according to the number of assessed anatomical structures)]. To evaluate potential differences between gender groups regarding the visibility of the TMJ's structures, Mann–Whitney *U* tests were

performed [significance level $\alpha = 0.05$, corrected for multiple comparisons ($n = 8$ according to the number of assessed anatomical structures)]. To assess the interreader agreement in the qualitative MR image analysis, Kappa-statistics was used. Kappa values of 0.41–0.60 were considered as moderate agreement, values of 0.61–0.80 were considered as substantial agreement, values of 0.81–0.99 were considered as almost perfect agreement and values of 1.00 were considered as perfect agreement.²⁵

Results

All images were successfully acquired. Specific absorption rate remained below individual limits in all sequences. No volunteer reported side effects during the scan.

Quantitative analysis

SNR analysis within the areas of interest (temporomandibular disc, the temporomandibular fossa and the temporomandibular condyle) yielded normal distribution for both field strengths (7.0 T, $p = 0.486$; 3.0 T, $p = 0.359$). The absolute SNR values were not different for both field strengths (mean $\pm$ SD; 7.0 T, 13.02 ± 3.92 ; 3.0 T, 14.02 ± 3.41 ; $p = 0.19$; Figure 2). There was no gender-specific difference in SNR at 7.0 T using dielectric pads (mean $\pm$ SD; females, 13.18 ± 4.31 ; males, 12.86 ± 3.68 ; $p = 0.85$) and at 3.0 T (mean $\pm$ SD; females, 14.23 ± 4.17 ; males, 13.82 ± 2.60 $p = 0.78$). According to the formula described in the Methods and materials section and taking all sequence parameters into account, the theoretical SNR difference between 3.0 T and 7.0 T is:

$$\frac{\text{SNR}_{7\text{ T}}}{\text{SNR}_{3\text{ T}}} = \sqrt{\frac{7}{3}} \frac{16}{25} = 0.98$$

This demonstrates that the whole SNR increase due to the higher B_0 has been invested in increased resolution together with similar water–fat shift.

Qualitative analysis

24 images of the TMJs of 12 subjects were compared between 7.0 T and 3.0 T with respect to the visibility of the anatomical structures of the TMJ (Table 2). Interreader agreement ranged from “substantial” to “almost perfect” for 7.0 T (0.63–0.84) and 3.0 T (0.76–0.87). For both readers, imaging the TMJ at 7.0 T yielded significantly increased visibility of all small anatomical structures, *i.e.* of the different zones of the temporomandibular disc, including the anterior band, the intermediate zone and the posterior band ($p < 0.05$, corrected for multiple comparisons; Table 2). It is to note that the visibility of the larger anatomical structures, namely the bilaminar zone, mandibular fossa, mandibular condyle and inferior pterygoid muscle was similar for both field strengths. Overall image quality

Figure 2 The signal-to-noise ratio (SNR) maps for images of the temporomandibular joint acquired at 7.0 and 3.0 T. For SNR analysis, data were calculated on a voxelwise basis for every coil channel using dedicated software routines, yielding voxel-based SNR maps. (a) Voxelwise SNR map for a representative volunteer at 7.0 T; (b) voxelwise SNR map for the same volunteer at 3.0 T. The SNR within the region of interest (temporomandibular disc, temporomandibular fossa and temporomandibular condyle) was similar for both field strengths. SNR values are colour coded from 0 (black) to 40 (white).

was not different when compared between 7.0 T and 3.0 T ($p < 0.05$, corrected for multiple comparisons; Figure 3 and Table 2). There was no statistically significant difference in the visibility of anatomical structures between female and male volunteers (Table 3, $p < 0.05$, corrected for multiple comparisons).

Discussion

In the current study, we found that imaging the TMJ at 7.0 T provides better visibility of small anatomical structures than standard-of-care 3.0-T MRI. This was mainly yielded by a higher spatial resolution while

Table 2 Visibility of different anatomical structures of the temporomandibular joint at 7.0 and 3.0 T and the corresponding between-group differences for both readers

Anatomical structure	7.0 T		3.0 T		7.0 T vs 3.0 T	
	Mean	SD	Mean	SD	p-value (uncorrected)	p-value (corrected)
Reader 1						
Temporomandibular disc						
Anterior band	1.29	0.46	2.17	0.38	0.000	0001*
Intermediate zone	1.46	0.51	2.21	0.42	0.000	0001*
Posterior band	1.58	0.58	2.46	0.59	0.000	0002*
Bilaminar zone	1.83	0.48	2.04	0.46	0.132	1000
Mandibular fossa	1.50	0.59	1.29	0.46	0.132	1000
Mandibular condyle	1.54	0.72	1.29	0.46	0.175	1000
Inferior pterygoid muscle	1.75	0.68	1.75	0.74	0.976	1000
Overall image quality	1.54	0.59	1.96	0.81	0.070	0559
Reader 2						
Temporomandibular disc						
Anterior band	1.33	0.48	2.13	0.34	0.000	0000*
Intermediate zone	1.50	0.51	2.17	0.38	0.000	0001*
Posterior band	1.54	0.51	2.42	0.58	0.000	0002*
Bilaminar zone	1.71	0.46	2.13	0.45	0.008	0060
Mandibular fossa	1.50	0.59	1.25	0.44	0.058	0462
Mandibular condyle	1.50	0.51	1.29	0.46	0.166	1000
Inferior pterygoid muscle	1.71	0.69	1.79	0.72	0.717	1000
Overall image quality	1.46	0.51	1.88	0.74	0.053	0425

SD, standard deviation.

Mean and SD are given for the visibility of each anatomical structure on a 5-point Likert scale ranging from 1 (excellent visibility and delineation) to 5 (complete lack of visibility) for both readers. For evaluation of the corresponding between-group differences, p -values are given uncorrected and as corrected for multiple comparisons. Asterisks indicate statistical significance after correction for multiple comparisons.

Figure 3 Qualitative analysis. Proton density weighted oblique sagittal images in closed mouth position at 7.0 and 3.0 T. (a) The sagittal image of a temporomandibular joint of an asymptomatic volunteer acquired at 7.0 T. (b) The image of the same temporomandibular joint of the same asymptomatic volunteer acquired at 3.0 T. For all subregions of the temporomandibular joint, visibility was statistically significant higher at 7.0 T.

overall SNR could be kept similar. Therefore, the current results suggest that imaging the TMJ at 7.0 T using high-permittivity dielectric pads might be feasible in clinical routine, and diagnosis of disc pathologies could be improved through a better visibility of the underlying anatomy.

High-permittivity dielectric pads

Until now, imaging the TMJ at 7.0 T was not performed due to considerable challenges, one of which is strong local transmit RF (B1+) inhomogeneities, causing an inhomogeneous flip angle distribution within the head, particularly with higher flip angles at the centre and lower flip angles at the lateral regions, overlapping with the areas covering the TMJ.¹⁸ Recently, Manoliu *et al*²⁰ solved this problem by using specifically tailored high-permittivity dielectric pads consisting of barium titanate in deuterated water, which can be used to mitigate the B1+ dropouts within the temporal bone at the cost of the global B1+ field.^{15,17,26} In the current study, identical high-permittivity dielectric pads were used to enable imaging the TMJ at 7.0 T. Our pads were differently designed for female and male volunteers to take gender-specific differences in head size into account. However, qualitative and quantitative analysis revealed no statistical between-gender differences. It is important to note that the pads can be used in practically all clinical setups, since their effect does not depend on the used hardware or software. Therefore, dielectric pads represent a convenient and economic approach to enable TMJ imaging at 7.0 T.¹⁵

Importantly, several other methods have been suggested to improve local B1+ fields,^{27–30} including static B1+ shimming and the application of dedicated RF pulse designs, such as adiabatic pulses and spatially tailored excitation designs.^{31,32} However, several issues, including the management of the specific absorption rate levels, are still challenging and need to be solved to ensure a safe application in clinical routine.^{15,33,34} Nevertheless, these approaches yield great potential for improving the image quality at 7.0 T and might make a significant contribution towards further optimization of 7.0 T TMJ imaging in the future.^{33–35}

Quantitative analysis

In the current study, we applied an intricate voxelwise approach to determine SNR for different field strengths *in vivo*. In contrast to other methods to assess SNR, such as calculating the ratio between the mean signal intensity and the corresponding standard deviation within a specific region of interest or the subtraction method, the current approach, which is based on a second scan without radiofrequency pulses and gradient switching, accounts for potential noise correlation among all coil channels and yields therefore robust voxelwise maps of the entire field of view.^{13,36,37} Our SNR analysis yielded similar SNR for both field strengths within the TMJ. The SNR was slightly lower for 7.0 T than for 3.0 T; however, this comparison yielded no statistically significant difference. In general, utilizing a higher magnetic field strength increases longitudinal magnetization, resulting in higher SNR due to an increased number of protons aligning along the main axis of the static magnetic field.¹³ However, the SNR depends also on many other variables, including the spatial resolution and sequence-specific parameters, such as TE and TR. Specifically, the SNR is positively correlated with voxelsize and TR and negatively correlated with TE. In our study, the SNR was compared at a higher spatial resolution for 7.0 T compared with 3.0 T using different sequence parameters (*i.e.* higher TR and lower TE for 7.0 T; Table 1). According to theoretical considerations and given all sequence parameters for both field strengths (particularly the higher spatial resolution), the SNR for 7.0 T is expected to be slightly lower than that for 3.0 T. Indeed, this trend was demonstrated in the SNR analysis, although statistical differences were not significant. Several additional aspects might have contributed to this observation: first, high-permittivity dielectric pads have been applied at 7.0 T only to mitigate the inhomogeneous flip angle distribution in the area surrounding the TMJ. Although a SNR gain has been demonstrated,²⁰ residual under- and overtipping effects regarding flip angle distribution might still slightly diminish the actual SNR. Second, the 32-channel head coil used at the 3.0-T system was based on the recently developed dStream

Table 3 Visibility of different anatomical structures of the temporomandibular joint at 7.0 and 3.0 T for females and males and the corresponding between-group differences

<i>Anatomical structure</i>	<i>Females</i>		<i>Males</i>		<i>Females vs Males</i>	
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>p-value (uncorrected)</i>	<i>p-value (corrected)</i>
<i>Reader 1</i>						
7.0 T						
Temporomandibular disc						
Anterior band	1.25	0.45	1.33	0.49	0.67	1.00
Intermediate zone	1.50	0.52	1.42	0.51	0.70	1.00
Posterior band	1.67	0.49	1.50	0.67	0.50	1.00
Bilaminar zone	1.75	0.62	1.92	0.29	0.41	1.00
Mandibular fossa	1.50	0.67	1.50	0.52	1.00	1.00
Mandibular condyle	1.42	0.67	1.67	0.78	0.41	1.00
Inferior pterygoid muscle	1.42	0.51	2.08	0.67	0.01	0.10
Overall image quality	1.33	0.49	1.75	0.62	0.08	0.66
3.0 T						
Temporomandibular disc						
Anterior band	2.33	0.49	2.00	0.00	0.03	0.23
Intermediate zone	2.33	0.49	2.08	0.29	0.14	1.00
Posterior band	2.58	0.67	2.33	0.49	0.31	1.00
Bilaminar zone	1.83	0.39	2.25	0.45	0.02	0.19
Mandibular fossa	1.17	0.39	1.42	0.51	0.19	1.00
Mandibular condyle	1.17	0.39	0.11		0.19	1.00
Inferior pterygoid muscle	1.75	0.87	1.75	0.62	1.00	1.00
Overall image quality	1.83	0.94	2.08	0.67	0.46	1.00
<i>Reader 2</i>						
7.0 T						
Temporomandibular disc						
Anterior band	1.25	0.45	1.42	0.51	0.41	1.00
Intermediate zone	1.50	0.52	1.50	0.52	1.00	1.00
Posterior band	1.67	0.49	1.42	0.51	0.24	1.00
Bilaminar zone	1.50	0.52	1.92	0.29	0.02	0.19
Mandibular fossa	1.42	0.51	1.58	0.67	0.50	1.00
Mandibular condyle	1.42	0.51	1.58	0.51	0.44	1.00
Inferior pterygoid muscle	1.42	0.51	2.00	0.74	0.04	0.28
Overall image quality	1.25	0.45	1.67	0.49	0.04	0.34
3.0 T						
Temporomandibular disc						
Anterior band	2.25	0.45	2.00	0.00	0.07	0.55
Intermediate zone	2.25	0.45	2.08	0.29	0.29	1.00
Posterior band	2.50	0.67	2.33	0.49	0.50	1.00
Bilaminar zone	2.00	0.43	2.25	0.45	0.18	1.00
Mandibular fossa	1.08	0.29	1.42	0.51	0.06	0.51
Mandibular condyle	1.17	0.39	1.42	0.51	0.19	1.00
Inferior pterygoid muscle	1.83	0.83	1.75	0.62	0.78	1.00
Overall image quality	1.67	0.78	2.08	0.67	0.17	1.00

SD, standard deviation.

Mean and SD are given for the visibility of each anatomical structure for both readers. Grading was based on a 5-point Likert-scale ranging from 1 (excellent visibility and delineation) to 5 (complete lack of visibility). For evaluation of the corresponding between-group differences, *p*-values are given uncorrected as well as corrected for multiple comparisons.

system (Philips Healthcare, Best, Netherlands), which digitalizes the acquired signal directly in the receive coil and transports it across broadband fibre optic cables, thus avoiding signal losses and noise pickups, which most likely improved the SNR at 3.0 T. This technique is still not available at 7.0 T.

Previously, it has been demonstrated that musculo-skeletal tissues yield different relaxation times at 7.0 and 3.0 T.¹⁹ Therefore, the TE and TR of newly designed sequences have to be chosen according to the T_1 and T_2 of different tissue types to evaluate the potential of clinical sequences at different field strengths.¹³ In the current study, all parameters have been selected in such a way that the whole SNR increase due to higher static magnetic field strength has been invested in higher

spatial resolution while keeping the water–fat shift similar, which was considered most beneficial for MRI of the TMJ. It is to note that this approach resulted in a longer TR at 7.0 T (3300 ms) than at 3.0 T (2700 ms), which explained the longer acquisition time at 7.0 T. Although this optimization ensured a good image quality, it is important to take into consideration that longer scan protocols bear the risk of increased patient movement. Naturally, the aforementioned gain in SNR could have been invested in increasing other parameters, which might be favourable when evaluating other anatomical regions of the dentomaxillofacial region.³⁸ In particular, decreasing the spatial resolution (*i.e.* decreasing the matrix size while keeping the field of view constant) and/or increasing the number of signal

averages (*i.e.* number of excitations) represent easy applicable methods to strongly increase SNR in regions where the spatial resolution obtained at 3.0 T is sufficient and/or which are not susceptible to movement artefacts. Finally, specific manufactured coils yield great potential in increasing SNR. Recently, Graessl *et al*³⁹ evaluated the performance of an individually constructed ophthalmic transmit/receive surface coil for MRI of the eye at 7.0 T and demonstrated that the application of coils may greatly improve MRI of delicate structures, such as the eye. Considering this observation, it can be assumed that MRI of the TMJ at 7.0 T might also greatly benefit from specifically tailored surface coils.

Taken together, considering all factors potentially modulating the SNR as well as their possible interactions is very challenging and was beyond the scope of the current study. Nevertheless, results suggest that the application of dielectric pads at 7.0 T enabled a robust and similar SNR when compared with 3.0 T while allowing for imaging of the TMJ, particularly the temporomandibular disc, at a higher spatial resolution.

Qualitative analysis

The visual assessment of the TMJ yielded “substantial” to “almost perfect” interreader agreement for the evaluated structures at 7.0 and 3.0 T. However, while at 3.0 T six out of eight evaluated structures yielded an “almost perfect” interreader agreement, at 7.0 T only the overall image quality showed an “almost perfect” interreader agreement, whereas the interreader agreement for all seven subregions of the TMJ was only “substantial”. This observation might be explained by the extensive experience of TMJ imaging at our hospital, whereas the personal experience of the two radiologists with the visual assessment of the TMJ at 7.0 T is still small and may require further routine.

In the current study, imaging the TMJ at 7.0 T yielded statistically increased visibility of the anterior band, intermediate zone and posterior band of the temporomandibular disc. It is to note that the visibility of the larger anatomical structures, such as the mandibular condyle, mandibular fossa and inferior pterygoid muscle did not benefit from imaging at 7.0 T. These results are well in line with the assumption that fine anatomical structures cannot be depicted in full detail at 3.0 T,^{7,12,19} whereas larger structures do not necessarily benefit from a higher spatial resolution. This observation also might explain why the overall image quality was rated similar for both field strengths. Nevertheless, presented results strongly suggest that imaging the TMJ at 7.0 T is superior to 3.0 T, especially when small anatomical structures are of particular interest.

Methodological considerations and limitations

We acknowledge several limitations of the current study as well as particular methodological considerations, which have to be taken into account when interpreting presented data. (i) *Dielectric pads*. The current study did not assess the impact of dielectric pads on B1+

inhomogeneity. However, the applied procedure followed strictly a recently published feasibility study comparing images acquired with and without dielectric pads at 7.0 T and assessing the B1+ characteristics in the presence of dielectric pads in full detail.²⁰ Therefore, no direct comparisons regarding images acquired with and without pads are presented in the current article. Furthermore, imaging of the TMJ at 3.0 T was performed without pads, further complicating the interpretation of reported findings. However, the dielectric pads used in the current study have been designed based on simulations for B1+ distribution at 7.0 T, therefore theoretical considerations suggest that their application at 3.0 T would not considerably improve image quality. Furthermore, the design of dedicated dielectric pads for 3.0 T was beyond the scope of the study, since B1+ dropouts in the region of the TMJ at 3.0 T are uncommon and dielectric pads with different permittivity properties would have further complicated the direct comparison between measured data at both field strengths. (ii) *Coils*. Currently, imaging of the TMJ is commonly performed using dedicated TMJ surface coils, whereas in this study only head coils were used. However, it has been demonstrated recently that MRI of the TMJ at 3.0 T using a 32-channel head coil yields superior visibility of the anatomical structures of interest as well as higher SNR compared with the broadly available 2-channel surface coil.²² Still, it is to note that the head coils used in this study were not identical. Although the head coil at 3.0 T was a receive-only coil, the head coil used at 7.0 T was a transmit/receive coil with a different local distribution of receive elements. Therefore, observed differences in image quality might at least be partially explained by different hardware specifications. (iii) *Scan sequences*. In the current study, only proton-density weighted images have been acquired. The main focus of the current study was to evaluate the potential advantage of imaging structures at 7.0 T, which might benefit most from imaging at a high spatial resolution, such as the temporomandibular disc. Indeed, the temporomandibular disc yielded significantly improved image quality at 7.0 T compared with 3.0 T, whereas other structures such as the mandibular condyle, which can already be well depicted at 3.0 T, did not profit from increased spatial resolution. Nevertheless, additional sequences would provide additional insights regarding the clinical potential of TMJ imaging at 7.0 T and should be investigated in further studies. Furthermore, the application of three-dimensional acquisitions might yield a great potential in a clinical context, particularly since the orientation of the correct axis can be very intricate. In the present study, however, we ensured a correct orientation by assuring a careful orientation of the acquired planes perpendicular to the transverse axis of the mandibular condyles according to recently reported studies.^{21,22} (iv) *SNR analysis*. When assessing a new sequence with respect to a potential clinical application at a new field strength, it is inherently necessary to optimize the imaging protocol with respect to the different relaxation times of musculoskeletal tissue at different static magnetic field

strengths.¹⁹ In the current study, selected sequence parameters, such as TE and TR have been chosen to fit different T_1 and T_2 values of specific tissues. However, it is to note that the TMJ consists of various tissue types with a heterogeneous difference between relaxation times at two different field strengths. Although results suggest that the chosen TR and TE might represent a good approximation, further standardized studies in phantoms and *in vivo* are necessary to fully understand the impact of different scan parameters on the assessed SNR. (v) *Scan planning*. In clinical examinations, MR images of the TMJ are often assessed in closed- and open-mouth position to evaluate potential alterations of the jaw motion. In line with the literature,^{20,22} we considered the evaluation of images in the closed-mouth position sufficient to infer possible benefits regarding image quality achieved using dielectric pads. However, the potential use of dielectric pads regarding dynamic scan sequences is still unclear and should be investigated in a further study. (vi) *Study sample*. It is to note that since this is the first study comparing MRI of the TMJ at 7.0 T using dielectric pads and 3.0 T, the anticipated effect size could not be inferred from current literature. Therefore, no power analysis was performed to estimate the required number of participants. However, data were consistent with low standard deviations. Thus, our quantitative and qualitative data may serve as basis for statistical power analysis for future larger clinical trials. Furthermore, the current study assessed asymptomatic healthy volunteers only. Although results demonstrate superior performance of MRI of the TMJ at 7.0 T compared with 3.0 T, further studies assessing patients with TMDs are necessary to fully appraise the potential clinical benefit of imaging the TMJ at 7.0 T. Please note that the IRB approval did not allowed inclusion

of patients. Thus, only asymptomatic volunteers could be included.

Clinical implications

Current MRI studies still provide only an unsatisfactory correlation between imaging findings and reported symptoms in patients with TMDs,⁷ which is assumed to be explained by the insufficient spatial resolution, which can be achieved at 1.5 or 3.0 T. In the current study, the application of a higher static magnetic field strength (*i.e.* 7.0 T) in combination with high-permittivity dielectric pads enabled an increased spatial resolution, finally yielding a superior visibility of temporomandibular disc in asymptomatic volunteers compared with 3.0 T. Current results strongly suggest that the achieved improvement in visibility of the temporomandibular disc might likely translate into a considerably improved diagnostic accuracy when evaluating potential pathologies underlying TMDs and have an impact on clinical decision making and therapeutic outcome for patients where MRI of the TMJ at 1.5 or 3.0 T is not sufficient to reveal the specific pathology causing clinical complaints. However, future studies including patients with various TMD-related pathologies are needed to provide clear evidence for the clinical practicability of the application of dielectric pads and/or the superior performance of imaging the TMJ at 7.0 T in a clinical context.

Conclusions

MRI of the TMJ at 7.0 T using high-permittivity dielectric pads at a higher spatial resolution yields similar SNR and increased visibility of small anatomical structures of the temporomandibular disc compared to 3.0 T.

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