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Diffusion-weighted MR neurography of the sacral plexus with unidirectional motion probing gradients

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Abstract Background: This technical note introduces diffusion-weighted (DW) MR neurography (MRN) of the sacral plexus with unidirectional motion probing gradients (MPGs).

Methods: This is compared with DW MRN with three-directional and six-directional MPGs. **Results and conclusion:** This paper indicates that DW MRN of the sacral plexus should be performed with unidirectional MPGs.

Keywords Diffusion-weighted imaging · Neurography · Peripheral nerve · Motion probing gradients · Sacral plexus

Introduction

Magnetic resonance (MR) imaging, using three-dimensional high-resolution fat-suppressed T2-weighted or T1-weighted sequences, is a useful technique for evaluating pathological conditions of the sacral plexus [1, 2]. Diffusion-weighted (DW) MR imaging (DWI) has recently been introduced as an alternative way to visualize nerves [3–5]. DW MR neurography (MRN) is based on the concept of diffusion-weighted whole-body imaging with background body signal suppression (DWIBS), which allows multiple thin-slice DWI data sets to be obtained [6]. Using this technique, structures of high signal intensity on fat-suppressed T2- and T1-weighted images adjacent to the nerves, such as veins, are well suppressed thanks to the use of motion probing gradients (MPGs), and the trajectory of the nerves is well visualized on maximum intensity projection (MIP) images. DW MRN is different from diffusion tensor imaging (DTI) in that it is just imaging of nerves and does not track the anisotropy of nerves [3–5]. Furthermore, for DW MRN, MPGs are usually applied in

no more than three different directions, whereas DTI requires a minimum of six different MPG directions [2–4]. However, the number of directions of MPGs that offers the best visualization of the nerves in DW MRN remains unknown. Theoretically, perpendicular positioning of the MPGs of a DWI sequence of the nerves offers the highest signal for them, as diffusion is relatively more impeded perpendicular to the nerve [7]. The purpose of this study was therefore to introduce DW MRN of the sacral plexus with unidirectional MPGs (anterior-posterior direction only) and to compare it with DW MRN with three-directional and six-directional MPGs.

Materials and methods

Subjects

Our institutional review board approved protocol optimization using volunteer subjects, and written informed consent was obtained from all subjects before the MR

examination. Five healthy volunteers [three men, two women, mean age 33.5 years (range, 23–45 years)] underwent DW MRN of the sacral plexus.

DW MRN

All subjects were examined with a 3.0-T MR unit (Achieva; Philips Healthcare, Best, The Netherlands) using a five-element phased-array surface coil. DW MRN was acquired using uni-, three- and six-directional MPGs. Imaging parameters are displayed in Table 1. Of note, image acquisition was performed in the axial plane, because, in our experience, direct coronal imaging tends to suffer from severe image distortion because of the requirement of a larger field of view. MR imaging was performed from the level of

the L4 nerve to the inguinal region, including the sciatic nerve, in all volunteers.

MIP post-processing

Two types of coronal MIP images were created: conventional (entire volume) and soap-bubble MIP images. Conventional MIP images included the entire part of the imaged area. Soap-bubble MIP images were generated by dedicated software (SoapBubble, release 5.0; Philips Healthcare). Soap-bubble software allows a curved sub-volume of the DW MRN data set to be obtained that closely encompasses the sacral plexus [4, 8]. In each volunteer, the reconstructed soap-bubble volume of DW MRN data sets obtained with uni-, three- and six-directional MPGs was identical. The reconstruction thickness of MIP images was 4 mm.

Image evaluation

Two board-certified radiologists blindly and independently evaluated DW MRN images obtained with uni-, three- and six-directional MPGs, and post-processed with conventional or soap-bubble MIP, using a four-grade scoring system (0 = nerve not visualized; 1 = a part of the nerve is visualized, but the maximum visualized length is less than 1 cm; 2 = nerve moderately well visualized; 3 = nerve clearly visualized), which was applied to the following segments of the sacral plexus: the anterior part of L4, L5, S1, S2, S3, S4 and the lumbosacral trunk, the conjoint part of the sacral plexus and the sciatic nerve.

Furthermore, one board-certified radiologist manually placed regions of interest (ROIs) in both the left and right lumbosacral trunks and sciatic nerves, and in the fat surrounding the nerves, on axial source images of DW MRN datasets obtained with uni-, three- and six-directional MPGs, with size and shape of ROIs being kept as equal as possible among the three sequences. The apparent signal-to-noise ratio (SNR) was calculated as $SI(\text{nerve})/SD(SI(\text{fat}))$, where $SI(\text{nerve})$ is the signal intensity (SI) of the nerve and $SD(SI(\text{fat}))$ is the standard deviation of the SI of surrounding fat. The apparent contrast-to-noise ratio (CNR) was calculated as $SI(\text{nerve})/SI(\text{fat})$, where $SI(\text{nerve})$ is the SI of the nerve and $SI(\text{fat})$ is the SI of surrounding fat.

Statistical analysis

Overall differences in visual scores with regard to depiction of sacral plexus segments according to applied DW MRN sequences (with uni-, three- or six-directional MPGs) and according to the applied post-processing method (conventional MIP or soap-bubble MIP) were assessed using the non-parametric Friedman

Table 1 Imaging parameters for DW MRN

Sequence	Single-shot EPI
Acquisition plane	Axial
FOV (mm)	350
Rectangular FOV percentage	80%
TR/TI/TE (ms)	12,664/250/80
EPI factor (ETL)	65
SENSE factor	2
Acquisition matrix	200×124
Phase encode reduction	80%
Half Fourier scan factor	0.805
Slice thickness/gap (mm)	4/0 (overlap)
Number of slices	70
B-value (s/mm^2)	800
Directions of MPGs	1 (AP only) 3 (three orthogonal axes, i.e., AP, LR and FH) 6 (three oblique axes added to three orthogonal axes)
Number of excitations	6 (at unidirectional MPGs) 2 (at three-directional MPGs) 1 (at six-directional MPGs)
Acquisition time (s)	203 ^a

Abbreviations and notes:

AP: anterior-posterior

EPI: echo-planar imaging

ETL: echo train length

FH: feet-head

FOV: field of view

LR: left-right

MPGs: motion probing gradients

TR: repetition time

TI: inversion time

TE: echo time

^aFor DW MRN at unidirectional MPGs, for DW-MRN at three-directional MPGs and for DW-MRN at six-directional MPGs

Fig. 1 Diffusion-weighted MR neurography (DW MRN) obtained with unidirectional MPGs and post-processed with soap-bubble MIP in volunteer 1, showing anatomical details of the sacral plexus. Bilateral nerve roots L4 to S3, lumbosacral trunk (LST) and sciatic nerve (SN) are visualized. The femoral nerve (FN), partly originating from nerve root L4, is also demonstrated

test. The non-parametric Wilcoxon test was used for paired comparisons when the overall comparison was significant.

Differences in mean SNRs and mean CNRs among the different DW MRN sequences (with uni-, three- or six-directional MPGs) were assessed by using one-way repeated-measures analysis of variance (ANOVA) with a Bonferroni post-hoc test.

The level of statistically significant difference was set at $P < 0.05$ for all tests. Statistical analyses were performed by using SPSS software, version 16.0 (SPSS, Chicago, IL).

Results

Anatomy of the sacral plexus on DW MRN

A representative example of DW MRN of the sacral plexus with unidirectional MPGs and post-processed with soap-bubble MIP is shown in Fig. 1.

Qualitative image evaluation

Qualitative scores are displayed in Table 2. The Friedman test revealed statistically significant differences in visual scores with regard to depiction of sacral plexus segments between the different DW MRN sequences and post-processing methods used, for both observer 1 (chi-squared 197.294, $df=5$; $P < 0.001$) and observer 2 (chi-squared 166.745, $df=5$; $P < 0.001$). Results of pairwise comparisons are displayed in Table 3. DW MRN obtained with unidirectional MPGs and post-processed with soap-bubble MIP was significantly better at visualizing the lumbosacral plexus than all other approaches ($P < 0.001$ for both observers). Overall visual scores (of both observers combined) for the visualization of the separate sacral plexus segments using DW MRN with unidirectional MPGs and post-processed with soap-bubble MIP are displayed in Table 4. All sacral plexus segments had an overall score of 2 or higher, except for the anterior divisions of the third and fourth sacral nerves (Table 4).

Quantitative image evaluation

Mean and median SNRs and CNRs are displayed in Table 5. The one-way repeated measures ANOVA revealed a significant overall effect of the type of DW MRN sequence used on both SNR ($F=87.692$, $df=2, 57$; $P < 0.001$) and CNR ($F=17.181$, $df=2, 57$; $P < 0.001$). Pairwise comparisons revealed that the mean SNR of DW MRN obtained with unidirectional MPGs was significantly higher than that of DW MRN obtained with three- and six-directional MPGs ($P < 0.001$ for both), and the mean SNR of DW MRN obtained with three-directional MPGs was significantly higher than that of DW MRN obtained with six-directional MPGs ($P < 0.001$). In addition, the mean CNR of DW MRN obtained with unidirectional MPGs was significantly higher than that of DW MRN obtained with three- and six-directional MPGs ($P < 0.003$ and $P < 0.001$), but mean CNR of DW MRN obtained with three-directional MPGs was not significantly different from that of DW MRN obtained with six-directional MPGs ($P=0.063$). A representative illustration of the results of the present study is displayed in Fig. 2.

Table 2 Mean and median visual scores of observer 1 and observer 2 with regard to depiction of sacral plexus segments using different diffusion-weighted MR neurography (DW MRN) sequences and post-processing methods

		Soap-bubble MIP			Conventional MIP		
		1D	3D	6D	1D	3D	6D
Observer 1	Mean $\pm$ SD	2.22 $\pm$ 1.04	1.71 $\pm$ 1.06	1.76 $\pm$ 1.05	1.41 $\pm$ 1.02	0.99 $\pm$ 0.76	1.00 $\pm$ 0.81
	Median	3	3	3	2	1	1
Observer 2	Mean $\pm$ SD	2.31 $\pm$ 1.03	1.94 $\pm$ 1.11	1.75 $\pm$ 1.19	1.65 $\pm$ 1.13	1.16 $\pm$ 1.00	1.00 $\pm$ 0.91
	Median	3	2	2	2	1	1

1D: unidirectional MPGs

3D: three-directional MPGs

6D: six-directional MPGs

Table 3 Pairwise comparisons of visual scores with regard to depiction of sacral plexus segments among the different DW MRN sequences and post-processing methods used

	1D-SB	3D-SB	6D-SB	1D-Conv	3D-Conv	6D-Conv
1D-SB		P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b
3D-SB			P=0.433 ^a P=0.041 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b
6D-SB				P<0.001 ^a P=0.245 ^b	P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b
1D-Conv					P<0.001 ^a P<0.001 ^b	P<0.001 ^a P<0.001 ^b
3D-Conv						P=0.847 ^a P=0.007 ^b
6D-Conv						

1D-SB: DW MRN obtained with unidirectional MPGs and post-processed with soap-bubble MIP

3D-SB: DW MRN obtained with three-directional MPGs and post-processed with soap-bubble MIP

6D-SB: DW MRN obtained with six-directional MPGs and post-processed with soap-bubble MIP

1D-Conv: DW MRN obtained with unidirectional MPG and post-processed with conventional MIP

3D-Conv: DW MRN obtained with three-directional MPGs and post-processed with conventional MIP

6D-Conv: DW MRN obtained with six-directional MPGs and post-processed with conventional MIP

a: Results from observer 1

b: Results from observer 2

Discussion

In the present study we showed that the visualization of the sacral plexus in DW MRN with unidirectional MPGs is superior to that of DW MRN with three-directional or six-directional MPGs. A comparison of DW MRN using three-directional and six-directional MPGs was previously made by Tsuchiya et al. [9], but this comparison was rather unfair because a longer scan time and a higher number of excitations were used for DW MRN with six-directional MPGs. In the present study, a fair comparison (i.e., equal image acquisition time and same effective number of excitations) was made between DW MRN using three-directional and six-directional MPGs, which showed that the former had an obvious tendency to better visualize the sacral plexus. In addition, and more importantly, this study shows that DW MRN with unidirectional MPGs is superior to DW MRN with both three-directional and six-directional MPGs in the same image acquisition time.

We propose two possible explanations for the superiority of DW MRN with unidirectional MPGs over DW MRN with three- or six-directional MPGs. First, DWI is prone to image distortion because of the use of echo-planar imaging [10], and the use of multi-directional MPGs may lead to different distortion directions. These different distortion directions may cause ineffective averaging of single-axis images to create the diffusion trace image, resulting in image blurring and signal decrease in the diffusion trace image. DW MRN with unidirectional MPGs does not have this disadvantage. Second, MPGs applied parallel to the peripheral nerves may not be effective at visualizing them, as diffusion is anisotropic in the human nervous system,

including the peripheral nerves [7]. In the present study, unidirectional MPGs were placed in the anterior-posterior direction, which is most perpendicular to the trajectories of the sacral plexus nerves.

In the present study, we also showed that, regardless of the number of MPGs used for DW MRN, the soap-bubble MIP approach is superior to the conventional MIP approach in visualizing the sacral plexus. The effectiveness of the soap-bubble MIP approach was previously shown in a feasibility study on DW MRN of the brachial plexus [4]. In summary, the soap-bubble technique allows projection of a user-defined curved subvolume, encompassing the entire nerve plexus, in a single plane; this enables visualization of the nerve plexus over its entire length and eliminates the superimposing of anatomical structures.

Table 4 Overall visual scores for the visualization of the separate sacral plexus segments using DW MRN with unidirectional MPGs and post-processed with soap-bubble MIP

Sacral plexus segment	Overall visual score
L4	2.35
L5	3.00
S1	3.00
S2	2.55
S3	1.35
S4	0.25
LST	2.75
Overall	2.90

LST: lumbosacral trunk

Table 5 Mean and median SNR and CNR according to DW MRN sequence used with uni-, three- or six- directional MPGs

		1D	3D	6D
SNR	Mean $\pm$ SD	6.55 $\pm$ 0.74	5.59 $\pm$ 0.53	3.88 $\pm$ 0.64
	Median	6.73	5.70	3.89
CNR	Mean $\pm$ SD	1.65 $\pm$ 0.25	1.36 $\pm$ 0.17	1.17 $\pm$ 0.33
	Median	1.59	1.38	1.03

1D: unidirectional MPGs

3D: three-directional MPGs

6D: six-directional MPGs

A limitation of the proposed DW MRN technique (unidirectional MPGs, soap-bubble MIP post-processing) is that the anterior divisions of the third and fourth sacral nerve were not always well visualized. Reducing the slice thickness may have allowed better visualization of these nerve roots, although at the expense of a prolonged

examination time. In addition, the use of more sophisticated multichannel systems and dedicated coils might further increase the quality of DW MRN images of the sacral plexus. Another limitation is that only healthy volunteers were included and that the clinical impact of the proposed DW MRN technique has not been evaluated yet in a patient population. Further research in a large series of patients is required. Additionally, it is not known whether the proposed DW MRN technique using unidirectional MPGs in the anterior-posterior direction only also performs well in the visualization of other peripheral nerves. Obviously, the course of the peripheral nerves is three-dimensional, and some peripheral nerves run relatively parallel to the anterior-posterior direction. Theoretically, these nerves are not well visualized when using unidirectional MPGs in the anterior-posterior direction only. Therefore, further evaluation of this new DW MRN approach in other parts of the body is necessary. Nevertheless, the significant increase in

Fig. 2 DW MRN post-processed with conventional (entire volume) MIP (left) and soap-bubble MIP (right), obtained with unidirectional (a, d), three-directional (b, e) and six-directional (c, f) MPGs. Quality of DW MRN images post-processed with soap-bubble MIP (d, e, f) is superior to that of corresponding images post-processed with conventional MIP (a, b, c). Quality of images with unidirectional encoding (a, d) is better than those with three-directional encoding (b, e) and those with six-directional encoding (c, f)

SNR we observed has encouraged us to obtain better DW MRN images even in other body parts.

In conclusion, the results of this study indicate that DW MRN of the sacral plexus should be performed with unidirectional MPGs. Post-processing the acquired DW MRN images with soap-bubble MIP yields better visualization of the sacral plexus than post-processing with conventional MIP.

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