Technical Note

Development of Three-Dimensional MR Neurography Using an Optimized Combination of Compressed Sensing and Parallel Imaging

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Declarations of interest

Masami Yoneyama is currently employed by Philips Japan. The other authors declare that they have no conflicts of interest.

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Abbreviations:

3D: three-dimensional

ANOVA: one-way analysis of variance

CI: confidence interval

CIDP: chronic inflammatory demyelinating polyneuropathy

CR: contrast-ratio

CS: compressed sensing

CS-SENSE: compressed sensing-sensitivity encoding

ETL: echo train length

FOV: field of view

ICC: intraclass correlation coefficients

iMSDE: improved motion-sensitized driven equilibrium

MIP: maximum intensity projection

MRCP: magnetic resonance cholangiopancreatography

MRN: Magnetic resonance neurography

ROI: regions of interest

SENSE: sensitivity-encoding

SNR: signal-to-noise ratio

STIR: short tau inversion recovery

TE: echo time

TOF-MRA: time-of-flight magnetic resonance angiography

TR: repetition time

TSE: turbo spin-echo

VISTA: volume isotropic turbo spin-echo acquisition

1. Introduction

Magnetic resonance neurography (MRN) is a useful for the evaluations of nerve shapes and nerve conditions [1-3], and it has been applied for the assessment of patients with diseases such as chronic inflammatory demyelinating polyneuropathy (CIDP) and Charcot-Marie-Tooth neuropathies [4-10]. MRN is commonly performed with a three-dimensional (3D) turbo spin-echo (TSE) sequence, which typically requires a long acquisition time (approx. 5–6 min). Sensitivity-encoding (SENSE) is a parallel imaging technique that is commonly used to reduce the acquisition time as a conventional method [2, 3]. However, the SENSE technique produces a noticeable increase in the noise signal due to the setting requiring a highly elevated reduction factor. In addition, the number of receive coils and their geometry in relation to the target lesion also affect the image quality and interpretation. In contrast, compressed sensing (CS)-SENSE (i.e. Compressed SENSE: CS-SENSE) is a more recently developed image acquisition and reconstruction method that combines the two techniques of CS and SENSE, and its clinical utility for various diseases has been extensively investigated [11-18].

Compressed sensing is a fast data-acquisition method that uses the sparsity of a target data set. CS-SENSE includes the SENSE algorithm effectively in the compressed sensing in its reconstruction process. The CS-SENSE technique has been described as an image acceleration technique with potentially higher acceleration and less reduction of the signal-to-noise ratio (SNR) compared to the conventional image acceleration technique. MRN mainly visualizes only the bright peripheral nerve signal, as recent acquisition techniques for MRN have successfully suppressed the background signals of vessels, fat and muscles using improved motion-sensitized driven equilibrium (iMSDE) pulse, short-tau inversion recovery (STIR) pulse, and T2 preparation pulse [2]. Therefore, MRN is expected to involve a certain degree of sparsity in its raw data, and the application of the CS-SENSE technique for the acquisition of MRN might be useful for its short acquisition time compared to the conventional SENSE technique. We conducted the present study to assess the MRN imaging quality obtained by the CS-SENSE technique with various acceleration factors in a comparison with the MRN imaging quality obtained by the conventional SENSE technique.

2. Materials & Methods

2.1. Subjects

The study was approved by our institutional review board, and written informed consent was obtained from all participants. Five healthy volunteers (5 men, mean age 26 years, age range 24–27) participated in this study after providing written informed consent.

2.2. Imaging protocol and scan parameters

All scanning was performed using a 3.0 Tesla MR-unit (Achieva TX; Philips Healthcare, Best, Netherlands) with a 16-channel neurovascular coil. Cervical MRN was obtained based on the 3D volume isotropic turbo spin-echo acquisition (VISTA) sequence with two types of prepulse, i.e., iMSDE for vessel suppression and STIR for fat suppression, by following a reported sequence design [2]. The MRN imaging parameters were as follows: repetition time (TR) 2200 ms, echo time (TE) 170 ms, echo train length (ETL) 50, echo spacing 7.3 ms, field of view (FOV) 300×300 mm, voxel size 1.17×1.18×2.00 mm, and number of slices 170. The scanning range in the z-axis was set from the skull base to the pulmonary apex. As post-processing, the coronal-based view in the antero-posterior direction was reconstructed by using the maximum intensity projection (MIP) algorithm; one MIP image in the coronal view (antero-posterior direction) using all acquired volumetric data was finally created as the MRN image for the evaluation. These post-processing applications were manually performed at the console of the MR unit by the radiologic technologist.

For the MRN image acceleration technique, we used the CS-SENSE and conventional SENSE respectively. CS-SENSE was introduced as an image reconstruction technique that consists of the combination of the CS and SENSE algorithms. More specifically, initially, in the process of k-space filling, variable-density incoherent under-sampling acquisition was performed to obtain the well-balanced signal distribution in both the center and peripheral k-space. Thereafter, the CS and SENSE algorithms were integrated to an iterative reconstruction loop. In this reconstruction loop, the 'SENSE unwrapping process' and the 'sparse transformation and denoising process' (usually performed in CS processing) were respectively and iteratively executed. This compressed SENSE algorithm is fully and automatically optimized to perform imaging, and these processes are appropriate in any condition for image reconstruction [19].

The CS-SENSE factors of 4, 8, 16 and 32 were respectively used. The scanning times of the respective CS-SENSE factors were as follows: CS-SENSE factor 4 (6' 47), 8 (3' 27), 16 (1' 46), and 32 (0' 53). As the reference standard for the comparison with CS-SENSE-based MRN, the conventional SENSE-based neurography was acquired using the SENSE factor of 4 with the scanning time 6' 25.

2.3. Quantitative analysis: Contrast ratio

In each of the MIP images, four 3-mm^2 regions of interest (ROI) were placed by a radiological technologist with 6 years of experience in neuroimaging who was blinded to the details of the image acquisition technique and its acceleration factors (Fig. 1). Each ROI was placed on cervical nerve roots nearly the ganglion bilaterally at the C7. An additional ROI as the background reference was placed on the trapezius muscle and/or soft tissue around the muscle. The same size, shape and location were used in ROI placement for all images in all subjects. In placing ROIs on images, manual correction of the location was performed when necessary. The mean signal intensity in each ROI was determined as the respective ROI's signal value. Finally, the contrast-ratio (CR) between the nerve and muscle was calculated as follows:

$$CR = [SI(nerve) - SI(muscle)]/[SI(nerve) + SI(muscle)]$$

where SI(nerve) is the signal intensity of the nerve, and SI(muscle) is the signal intensity of the muscle. As supportive analysis of quantitative evaluation, we also performed measurements of the contrast-to-noise ratio (CNR) using the abovementioned ROIs with reference to the previously described method and the following equation [20].

$$CNR = [SI(nerve) - SI(muscle)]/[N(nerve)^2 + N(muscle)^2]^\wedge(\frac{1}{2})$$

where N(nerve) and N(muscle) is the noise in nerve and muscle respectively. Noise was defined as the standard deviation of signal intensity within the ROI.

2.4. Qualitative analysis: Visual assessment

The image quality of the depicted cervical brachial plexus was visually evaluated based on the degree of the depiction of the nerve sheath compared to the background signal, using the following three-point grading system. 1: poor visibility of the nerve sheath (difficult to evaluate), and/or severe blurring other artifacts; 2, moderate visibility of the nerve sheath (evaluable, but with non-optimal visibility) and/or a mild degree of blurring or other artifacts; 3, good visibility of the nerve sheath (easily evaluable) with almost no blurring or other artifacts. Representative nerve sheath depiction in each score was presented in Fig. 2. A total of five experienced radiologic technologists provided qualitative analysis for each MRN image; all were blinded to the details of image acquisition technique and its acceleration factors.

2.5. Clinical case evaluation

Several clinical cases for whom images were acquired using the specific CS-SENSE reduction factor were visually evaluated. The specific CS-SENSE reduction factor was selected from the result of CR value analysis as follows; we selected the highest CS-SENSE reduction factor among MRN images which showed no significant differences or significantly higher in CR value compared to conventional SENSE-based MRN (see statistical analysis below). A board-certified radiologist with 14 years of experience in neuroradiology evaluated each case to classify a sufficient or insufficient image quality for diagnostic use.

2.5. Statistical analysis

First, we calculated the intraclass correlation coefficients (ICC) among five raters in assessing the visual scores of MRN images in the qualitative assessment.

To determine the degree to which the CS-SENSE reduction factor could be elevated while maintaining its image quality equivalent to that of conventional SENSE-based MRN, we performed a multiple comparison between the MRN obtained with various CS-SENSE reduction factors and the conventional SENSE-based MRN. For both of two comparisons, i.e., using the quantitative CR values, CNR values, and using the qualitative visual scores, we performed a one-way analysis of variance (ANOVA) and Dunnett's test for the multiple comparison with the SENSE-based MRN used as the reference standard.

We also calculated the ratio of CR values, CNR values and the visual scores obtained from the CS-SENSE-based MRN to those obtained from the SENSE-based MRN, and obtained the 95% confidence intervals (CIs) of these ratios.

All statistical analyses were performed using JMP® pro 14 software (SAS, Cary, NC, USA) and BellCurve for Excel (Social Survey Research Information, Tokyo). Statistical significance was set as $p<0.05$ for all tests.

3. Results

All MRN scanning was successfully performed without any complications. The value of ICC among the five raters in the qualitative assessment was 0.92 (95%CI: 0.88–0.95).

In the quantitative analysis, the CR values obtained with the CS-SENSE factors of 4, 8, 16, and 32 were 0.54 ± 0.05, 0.53 ± 0.04, 0.49 ± 0.04, and 0.40 ± 0.06, respectively. The CR value obtained with the conventional SENSE-based MRN was 0.54 ± 0.05. In addition, the CNR values obtained with CS-SENSE factors of 4, 8, 16, and 32 were 3.06 ± 0.59, 2.82 ± 0.54, 1.82 ± 0.34, and 1.04 ± 0.15, respectively. The CNR value obtained with the conventional SENSE-based MRN was 2.34 ± 0.58.

In the qualitative visual assessment, the respective scores obtained with the CS-SENSE factors of 4, 8, 16, and 32 were 2.92 ± 0.28, 2.88 ± 0.33, 2.72 ± 0.46, and 2.00 ± 0.50, respectively, whereas the visual score obtained with the conventional SENSE-based MRN was 3.00 ± 0.00.

In the multiple comparison among MRN images with various sets of CS-SENSE and SENSE factors with the reference of conventional SENSE-based MRN, Dunnett's test revealed that the quantitative CR values obtained with the CS-SENSE factors of 16 and 32 were significantly lower compared to that obtained with the conventional SENSE-based MRN. In addition, the quantitative CNR values obtained with the CS-SENSE factors of 4 and 8 were significantly higher than that obtained with the conventional SENSE-based MRN while the CS-SENSE factor of 32 was significantly lower. The qualitative visual scores obtained with the CS factors of 32 and 16 were also significantly lower than that obtained with the conventional SENSE-based MRN.

The ratio of the mean CR value of MRN with the CS-SENSE factors 4, 8, 16, and 32 to the conventional SENSE-based MRN and its 95%CI were as follows: CS-SENSE factor 4 (1.00, 95%CI: 0.93–1.08), factor 8 (0.99, 95%CI: 0.93–1.06), factor 16 (0.91, 95%CI: 0.85–0.99) and factor 32 (0.74, 95%CI: 0.67–0.81). The ratio of the mean CNR value of MRN with the CS-SENSE factors 4, 8, 16, and 32 to the conventional

SENSE-based MRN and its 95%CI were as follows: CS-SENSE factor 4 (1.31, 95%CI: 1.13–1.61), factor 8 (1.21, 95%CI: 1.12–1.35), factor 16 (0.78, 95%CI: 0.65–1.02) and factor 32 (0.44, 95%CI: 0.37–0.66). In addition, the ratio of the mean visual score of MRN with the CS-SENSE factors 4, 8, 16 and 32 to the conventional SENSE-based MRN and its 95%CI were as follows: CS-SENSE factor 4 (0.97, 95%CI: 0.94–1.03), factor 8 (0.96, 95%CI: 0.91–1.01), factor 16 (0.91, 95%CI: 0.84–0.97) and factor 32 (0.67, 95%CI: 0.60–0.74). For CS-SENSE factors of 4 and 8, all ratios of the CS-SENSE-based MRN values for CR, CNR and visual scores to those from SENSE-based MRN were above 0.95.

The details of the CR values, CNR values, and visual scores are respectively presented in Table 1, Table 2, and Table 3. Representative MRN images with all reduction factors obtained with the conventional SENSE technique and the CS-SENSE technique are provided in Fig. 3.

In the clinical case evaluation, based on the results of statistical analysis (see above), a CS-SENSE factor of 8 was used for image acquisition. MRN images in three patients with CIDP were visually evaluated by a board-certified neuroradiologist. All images were deemed as having sufficient visibility (Fig. 4).

4. Discussion

Our findings suggest that the image quality of MRN with the CS-SENSE factor of 8 could be well-maintained, evaluated both quantitatively and qualitatively, compared to the conventional SENSE-based MRN with a long scanning time, whereas the MRN with the CS-SENSE factors of 16 and 32 showed lower image quality in several of the quantitative and qualitative visual assessments. CS-SENSE-based MRN can provide sufficient image quality with fast scanning (approx. one-half of the acquisition time) with the acceleration factor of 8 compared to conventional SENSE-based MRN. In addition, CS-SENSE-based MRN with the acceleration factor of 8 achieved sufficient image quality not only in healthy subjects but also in several clinical cases.

In earlier studies, the utility of the CS technique was described mostly for the acquisition of images with techniques such as time-of-flight magnetic resonance angiography (TOF-MRA) and magnetic resonance cholangiopancreatography (MRCP), which are considered to have high sparsity in their image raw data [21-28] because the denoising system in the CS algorithm has been considered more effective when this algorithm was used for the acquisition of images with such sparsity in its image raw data. Recent acquisition techniques of MRN depict the nerve structure as a bright signal while background signals are suppressed by organized preparation pulses in the MRN sequence design [2]. From this point of view, MRN resembles images obtained by TOF-MRA or MRCP. We thus speculated that MRN might be compatible with CS-SENSE for a shortened scanning time with a higher acceleration factor.

The clinical utility of MRN for the assessment of peripheral nerve diseases has been well described [4–10]. However, conventional MRN generally requires a scanning time of ~5–6 min to obtain images with sufficient visualization of peripheral nerves. Such a long scan time might involve unavoidable movement(s) by the patient during scanning and thus result in overall poor image quality with an unclear depiction of peripheral nerves. Patients with typical neurological symptoms such as tremor are especially likely to produce motion artifacts during imaging. The shorter scanning time of MRN with the CS-SENSE might be helpful in addressing this problem. The faster scanning that is enabled by the use of the CS-SENSE technique has the potential to achieve superb image quality with limited motion artifacts. It may also be possible to add MRN with CS-SENSE-based scanning to all routine assessments of the cervical spine for various screening purposes if the MRN can be completed within a short scanning time (e.g., a few minutes).

Although we observed herein that the CS-SENSE-based MRN with the CS-SENSE factor of 16 resulted in a lower CR value and a lower visual score, the ratios of the CR value and the visual score between the CS-SENSE-based and conventional SENSE-based MRN were both above 0.9; even the CS-SENSE factor of 16 may be successfully used with acceptable image quality if the acquisition is performed for screening purposes.

This study has several limitations. The number of subjects was quite small (n=5). However, the quantitative analysis of the CR showed a very small range of standard deviation in all of the subjects' analyses. We believe that the tendency of the results would not differ in an analysis with a large number of subjects. In addition, we analyzed only healthy subjects. The depictions of peripheral nerves between normal and abnormal subjects can be expected to differ to some degree. Further analyses of the utility of CS-SENSE-based MRN in patients with cervical nerve diseases are needed.

In conclusion, CS-SENSE-based MRN can be accomplished with a fast scanning time and sufficient image quality when using the high acceleration factor of 8. This technique will useful for daily examinations of the cervical spinal cord or spine in clinical practice.

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Table Captions and Figure Legends

Table 1. Contrast ratios (CRs) in conventional SENSE and CS-SENSE-based MRN

Technique	acceleration factor	CR value	Ratio of CR value to conventional SENSE based MRN (95% CI)
Conventional SENSE based MRN	4	0.54±0.05	-
CS-SENSE based MRN	4	0.54±0.05	1.00 (0.93-1.08)
	8	0.53±0.04	0.99 (0.93-1.06)
	16	0.49±0.04	0.91 (0.85-0.99)
	32	0.4±0.06	0.74 (0.67-0.81)

Table 1 footnote: The CR data are mean ± standard deviation (SD). CR: contrast ratio, 95% CI: 95% confidence intervals.

Table 2. Contrast-to-noise ratios (CNRs) in conventional SENSE and CS-SENSE-based MRN

Technique	acceleration factor	CNR value	Ratio of CNR value to conventional SENSE based MRN (95% CI)
Conventional SENSE based MRN	4	2.34±0.58	-
CS-SENSE based MRN	4	3.06±0.59	1.31 (1.13-1.61)
	8	2.82±0.54	1.21 (1.12-1.35)
	16	1.82±0.34	0.78 (0.65-1.02)
	32	1.04±0.15	0.44 (0.37-0.66)

Table 2 footnote: The CNR data are mean ± standard deviation (SD). CNR: contrast-to-noise ratio, 95% CI: 95% confidence intervals.

Table 3. Visual scores in conventional SENSE and CS-SENSE-based MRN

Technique	acceleration factor	visual score	Ratio of visual score to conventional SENSE based MRN (95% CI)
Conventional SENSE based MRN	4	3.00±0.00	-
CS-SENSE based MRN	4	2.92±0.28	0.97 (0.94-1.03)
	8	2.88±0.33	0.96 (0.91-1.01)
	16	2.72±0.46	0.91 (0.84-0.97)
	32	2.00±0.5	0.67 (0.60-0.74)

Table 3 footnote: The visual scores are mean ± SD. 95% CI: 95% confidence intervals.

Fig. 1. Example of ROI placement. In the MRN images, four 3-mm^2 ROIs were placed on cervical nerve roots near the ganglion at the C7. MRN images (dotted line squares). ROIs on the trapezius muscle and/or soft tissue around the muscle were also placed as a reference for the background signal (solid line squares).

Fig. 2. The degree of depiction of the cervical nerves compared to the background signal on MRN images was classified using a three-point grading system. 1: poor, overall poor visibility **(a)**. 2: moderate, well visibility but partly poor **(b)**. 3: good, overall good visibility **(c)**.

Fig. 3. Representative MRN images obtained with conventional SENSE **(a)** and CS-SENSE with reduction factors of 4 **(b)**, 8 **(c)**, 16 **(d)** and 32 **(e)**.

Fig. 4. MRN images of clinical cases acquired with a CS-SENSE reduction factor of 8. Three cases with MRN images are presented: (a) an 18-year-old male, (b) a 54-year-old male, and (c) a 51-year-old female; all were patients diagnosed with chronic inflammatory demyelinating polyneuropathy (CIDP). Enlarged cervical nerves were clearly visualized with sufficient image quality in all images.