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High-resolution MRI using compressed sensing-sensitivity encoding (CS-SENSE) for patients with suspected neurovascular compression syndrome: comparison with the conventional SENSE parallel acquisition technique

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AIM: To retrospectively compare sensitivity encoding (SENSE) and compressed sensing-sensitivity encoding (CS-SENSE) for high resolution (HR) cranial nerve magnetic resonance imaging (MRI) in a clinical population.

MATERIAL AND METHODS: Twenty consecutive patients who were clinically suspected of neurovascular compression syndrome (NVCS) were enrolled in this study. HR three-dimensional isotropic T2-weighted fast spin-echo (T2 VISTA) sequences with SENSE or CS-SENSE, and contrast-enhanced three-dimensional T1-turbo field-echo (CE 3D T1 TFE) with SENSE or CS-SENSE, were compared using quantitative and qualitative methods by two board-certified neuroradiologists.

RESULTS: For the T2 VISTA, CS-SENSE was significantly superior to SENSE in terms of cerebrospinal fluid homogeneity. For CE 3D T1 TFE, CS-SENSE was significantly superior to SENSE in terms of the existence of ghost artefact and the signal-to-noise ratio (SNR) of the pontine parenchyma. There was no significant difference in overall image quality between the two techniques. Compared with SENSE, CS-SENSE reduced the scan time to 44.2% of that with SENSE on T2 VISTA, and to 66.1% of that with SENSE of the CE 3D T1 TFE, with the differences being statistically significant ($p<0.01$, both).

CONCLUSION: For T2 VISTA and CE 3D T1 TFE imaging of patients with suspected NVCS, CS-SENSE appears to offer superior reductions in motion artefact and scan time relative to SENSE, without a loss of overall image quality.

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Introduction

Neurovascular compression syndrome (NVCS) covers a range of symptomatic cranial nerve diseases induced by contact with and mechanical irritation from vessels.[1,2] The main role of magnetic resonance imaging (MRI) is to demonstrate contact with a vessel at the root entry/exit zone (REZ) of the symptomatic cranial nerve, or combined displacement and atrophy of the nerve.[2–4] As the cranial nerves are fine structures, high-resolution (HR) three-dimensional (3D) images are currently considered optimal for the diagnosis.[1,4–7] Even though HR-3D-MRI provides high spatial resolution and excellent soft-tissue contrast, motion artefact resulting from the long scan time can cause degradation of image quality, which is an important issue in daily practice.[8] Therefore, image-acquisition and reconstruction techniques including parallel imaging and compressed sensing (CS) have been developed to reduce the scan time while preserving image quality.[9] Conventional parallel imaging techniques such as sensitivity encoding (SENSE) and generalised auto-calibrating partial parallel acquisition (GRAPPA) are still limited in their ability to simultaneously achieve scan time reduction and adequate image quality or scan range.[10,11] Recently, researchers have focused on the use of CS and have demonstrated that CS is an acceptable technique that can reduce scan time by non-uniform sampling of k-space, known as representative under-sampling technique, followed by wavelet transform and iterative reconstruction techniques to compensate for the drawbacks.[12,13] In addition, combined SENSE and CS techniques such as CS-SENSE have been newly developed, and these can lead to image-acquisition acceleration factors that far exceed those achievable by either parallel or CS techniques alone.[14] Despite these techniques having the potential to not only decrease scan time, but also preserve image quality, clinical verification of these techniques is essential before their broader implementation into daily practice. A small number of recent clinical studies have evaluated the performance of CS-SENSE in body[15,16] and brain imaging,[14,17,18] but to the authors' knowledge, no study has shown the effect of CS-SENSE on the HR-MRI of the cranial nerve or an NVCS clinical population. Therefore, the present study was undertaken to compare image quality and scan time between SENSE and CS-SENSE in 3D isotropic T2-weighted fast spin-echo (T2 VISTA) and contrast-enhanced 3D T1-turbo field-echo (CE 3D T1 TFE) sequences of patients with NVCS.

Material and methods

This retrospective study was approved by the institutional review boards and the requirement for informed consent for data evaluation was waived. The methods and reporting of the results are in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement.[19]

Study population

The study population was obtained from consecutive adult patients who were clinically suspected of NVSC according to their symptoms and physical examinations (range: cranial nerve 5th to 8th) and underwent pretreatment HR-MRI at Asan Medical Center (2,700 bed) academic tertiary referral hospital in Seoul, Korea, between June 2018 and August 2018. Patients with (a) a contraindication to MRI examination; (b) prior operation history in intracranial or head and neck areas; and (c) clinical suspicion of other disease. Finally, 20 patients were enrolled in the study.

Imaging protocol

All MRI examinations were obtained using a 3 T system (Ingenia CX, Philips Medical Systems, Best, the Netherlands) with a 32-channel sensitivity-encoding head coil. CS-SENSE is a newly developed technique combining CS and SENSE. Each T2 VISTA and CE 3D T1 TFE sequence was acquired with SENSE or CS-SENSE acceleration. The imaging parameters for the T2 VISTA sequence with both SENSE and CS-SENSE included 221 ms echo time, 2,000 ms repetition time, two excitations, 90° flip angle, 300×300×80 matrix, 180×180×48 mm field of view, 0.5×0.5×1.2 mm acquisition voxel size, 0.35×0.35×0.6 mm reconstructed voxel size, and no fat saturation. The SENSE imaging used a SENSE factor of 1 as a default baseline value, while the CS-SENSE used an acceleration factor of 5.5. The imaging parameters for the CE 3D T1 TFE using Gd-DOTA (Dotarem; Guerbet, Paris, France) at 0.2 mmol/kg of body weight included 3.6 ms echo time, 7.3 ms repetition time, one excitation, 8° flip angle, 360×360×80 matrix, 180×180×48 mm field of view, 0.5×0.5×1.2 mm acquisition voxel size, 0.35×0.35×0.6 mm reconstructed voxel size and fat saturation. The SENSE imaging used a SENSE factor of 1 as a default baseline value, and the CS-SENSE used an acceleration factor of 1.5.

MRI image analysis

MRI images were reviewed using a picture archiving and communications system (PACS). For the qualitative analysis, two board-certified neuroradiologists with 9 and 4 years of head and neck radiology experience independently assessed randomised image sets. The chief complaints about the cranial nerve symptoms of the patients were provided to the radiologists. Before evaluation, the two neuroradiologists completed a training session with five patients to help them reach a consensus on evaluation of the imaging findings. The T2 VISTA and CE 3D T1 TFE were rated using a five-point visual scoring system for overall image quality (1: very poor, image not usable for interpretation; 2: poor, relevant limitations for image interpretation; 3: adequate, moderate limitations for image interpretation; 4: good, minimal limitations for image interpretation; 5: excellent, no limitations for image interpretation) and vessel and nerve discrimination (1: very poor, hard to discriminate; 2: poor, severe blurring; 3: adequate, moderate blurring; 4: good, total

visualisation with mild blurring; 5: excellent, total visualisation without blurring).[20] The homogeneity of the cerebrospinal fluid (CSF) space was evaluated on T2 VISTA sequences (1: very heterogeneous, image not usable for interpretation; 2: heterogeneous, relevant limitations for image interpretation; 3: adequate, moderate limitations for image interpretation; 4: homogeneous, minimal limitations for image interpretation; 5: excellent homogeneity, no limitations for image interpretation).[21] Additionally, the existence or absence of MRI ghost artefact was evaluated on CE 3D T1 TFE.

For the quantitative evaluation of image quality, one board-certificated neuroradiologist with 4 years of head and neck radiology experience made signal-to-noise ratio (SNR) measurements in the mid pons (region of interest area 2×2 cm). The $SNR_{pontine\ parenchyma}$ was then calculated as: SNR = 0.695×(signal intensity)/(noise), with noise being measured as the standard deviation of the white matter signal in the middle cerebellar peduncle (region of interest area >200 mm^2).[22] Furthermore, to objectively evaluate the discrimination of vessels, the contrast-to-noise ratio (CNR) between the CSF space and artery was calculated as: $(CNR_{csf\text{-}artery}) = SNR_{csf} - SNR_{artery}$. Likewise, to evaluate the discrimination of nerves, the CNR between the CSF and nerve was calculated as: $(CNR_{csf\text{-}nerve}) = SNR_{csf} - SNR_{nerve}$.[23]

The MRI criterion of neurovascular compression syndrome was defined as any vessel making contact with the symptomatic target cranial nerve (1) at the REZ, or (2) causing displacement or (3) atrophy.[1,2,4]

Statistical analysis

This study had two outcomes: the image quality and the scan acquisition time. Image quality was measured by the quantitative and qualitative methods described above. The Kolmogorov–Smirnov test was used to determine whether the continuous variables were normally distributed. According to the results of the Kolmogorov–Smirnov test, either a paired *t*-test or a Wilcoxon rank analyses were performed between the SENSE and CS-SENSE. Interobserver agreement for the qualitative evaluation of image quality was calculated using Cohen's kappa analysis for nominal variables, and weighted kappa analysis for ordinal variables including the five-point visual scoring systems. The strength of the interobserver agreement according to the weighted kappa was categorised as follows: <0.20, poor; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, good; 0.81–1.00, excellent.[24] The overall proportion of agreement between the SENSE and CS-SENSE was obtained. MedCalc software (MedCalc for Windows, Version 17.8.6.; MedCalc Software, Mariakerke, Belgium) was used for the analysis, with a *p*-value of 0.05 considered statistically significant.

Results

The 20 patients enrolled in this study had a mean age of 52.9 years (range, 29–72 years), and eight were men and 12 were women. Six of 20 had symptoms relieved by decompression surgery. Their baseline characteristics are summarised in Table 1.

Table 1
Patient demographics, neurovascular compression syndrome characteristics, and clinical data.

Parameters	
Patient (male:female), *n*	20 (8:12)
Age, mean (min., max.), years	52.9 (29, 72)
Target cranial nerves, *n*	
Trigeminal nerve	10
Facial nerve	10
Laterality (right, left), *n*	11:9
Positive NCVS diagnosis on MRI	
SENSE	13/20
CS-SENSE	12/20
Overall proportion of agreement between SENSE and CS-SENSE	95% (19/20)

CS-SENSE, compressed sensing–sensitivity encoding; min., minimum; max., maximum; NVCS, neurovascular compression syndrome; SENSE, sensitivity encoding.

Table 2 shows the clinical outcomes of this study. In the qualitative image analysis, CS-SENSE was significantly superior to SENSE in terms of CSF homogeneity ($p<0.05$) on T2 VISTA, and in terms of the existence of ghost artefact ($p<0.001$) on CE 3D T1 TFE; however, there were no

Table 2
Comparison of clinical outcomes between SENSE and CS-SENSE.

Parameters	SENSE	CS-SENSE	*p*-value
Qualitative analysis			
T2 VISTA			
Overall image quality	4.2±0.5	4.2±0.5	0.16
Vessel discrimination	4.6±0.5	4.5±0.4	0.11
Nerve discrimination	4.6±0.5	4.6±0.5	>0.99
CSF homogeneity	3.6±0.5	3.9±0.4	<0.05
CE 3D T1 TFE			
Overall image quality	3.8±0.4	3.7±0.5	0.81
Vessel discrimination	3.9±0.4	3.9±0.4	>0.99
Nerve discrimination	3.9±0.6	3.9±0.6	>0.99
Ghost artefact, percentage	18/20	1/20	<0.01
Quantitative analysis			
T2 VISTA			
$SNR_{pontine\ parenchyma}$	4.1±1.1	3.6±0.9	0.94[a]
$CNR_{csf\text{-}artery}$	53.1±9.4	57.6±11.4	0.1[a]
$CNR_{csf\text{-}nerve}$	51.9±9.7	55.5±11.7	0.21[a]
Scan time, seconds	482	218	<0.01
CE 3D T1 TFE			
$SNR_{pontine\ parenchyma}$	13.4±1.8	14.8±5.4	<0.01[a]
$CNR_{csf\text{-}artery}$	32.4±5.5	30.9±6.7	0.18[a]
$CNR_{csf\text{-}nerve}$	7±2.1	7.5±1.5	0.08[a]
Scan time, seconds	242.3±6	160.1±2.4	<0.01

The data presented are mean±standard deviation.
In brief, the five-point scale for visual scoring of overall image quality is as follows: 1, very poor; 5, excellent; for vessel and nerve discrimination: 1, very poor; 5, excellent; and for CSF homogeneity: 1, very heterogeneous; 5, excellent homogeneity.
CNR, contrast-to-noise ratio; CSF, cerebrospinal fluid; CE 3D T1 TFE, contrast enhanced three dimensional T1-turbo field-echo; CS-SENSE, compressed sensing–sensitivity encoding; SENSE, sensitivity encoding; SNR, signal-to-noise ratio; T2 VISTA, three-dimensional isotropic T2-weighted fast spin-echo.
[a] *p*-Value obtained by paired *t*-test, the others were obtained by Wilcoxon rank analysis.

significant differences between SENSE and CS-SENSE in the overall image quality, vessel discrimination, and nerve discrimination on either T2 VISTA or CE 3D T1 TFE. In the quantitative image analysis, $SNR_{\text{pontine parenchyma}}$ on CE 3D T1 TFE was significantly higher with CS-SENSE than with SENSE ($p<0.01$). The other quantitative image analysis parameters showed no significant differences between SENSE and CS-SENSE. Compared with SENSE, CS-SENSE reduced the scan time to 44.2% of that with SENSE on T2 VISTA, and to 66.1% of that with SENSE of the CE 3D T1 TFE, with the differences being statistically significant ($p<0.01$, both). The two observers showed fair interobserver agreement on the five-point visual scoring system (weighted kappa, 0.450–0.621), and moderate agreement in the nominal variables, including the existence of ghost artefact on CE 3D T1 TFE and positive NVCS diagnosis on MRI (Cohen's kappa, 0.636–0.913). Representative T2 VISTA and CE 3D T1 TFE images are presented in Figs 1 and 2, respectively.

Discussion

The present study compared CS-SENSE and SENSE with respect to the image quality and scan time of HR-MRI of the cranial nerve in patients with clinically suspected NVCS. The overall image quality was similar between CS-SENSE and SENSE. CS-SENSE images were significantly superior to SENSE in terms of CSF homogeneity on T2 VISTA and the existence of ghost artefact on CE 3D T1 TFE. The SNR of the pontine parenchyma was significantly higher with CS-SENSE than with SENSE on CE 3D T1 TFE. Above all, CS-SENSE reduced the scan time to 44.2% of that with SENSE on T2 VISTA, and to 66.1% of that with SENSE of the CE 3D T1 TFE, compared with SENSE with the differences being statistically significant ($p<0.01$, both). The present results suggest that the use of CS-SENSE in routine practice could reduce motion artefact by reducing the required scan time. Although many studies in the field of neuroradiology have covered the acquisition of HR 3D MRI images, to the authors' knowledge[14,17] this is the first study to apply CS-SENSE to HR-MRI of the cranial nerve in a clinical patient population.

NVCS is a symptomatic cranial nerve disease induced by mechanical irritation from vessels. It is one of the major causes of trigeminal neuralgia (cranial nerve V), hemifacial spasm (cranial nerve VII), vestibular paroxysmia (cranial nerve VIII), and glossopharyngeal neuralgia (cranial nerve IX).[1,2] The major role of MRI in NVSC is to demonstrate direct contact of a vessel with the REZ of the symptomatic cranial nerve, or to show nerve displacement by a vessel or atrophy.[2–4] Combinations of HR-3D heavily T2WI, CE-T1WI, and time-of-flight images are generally considered as the

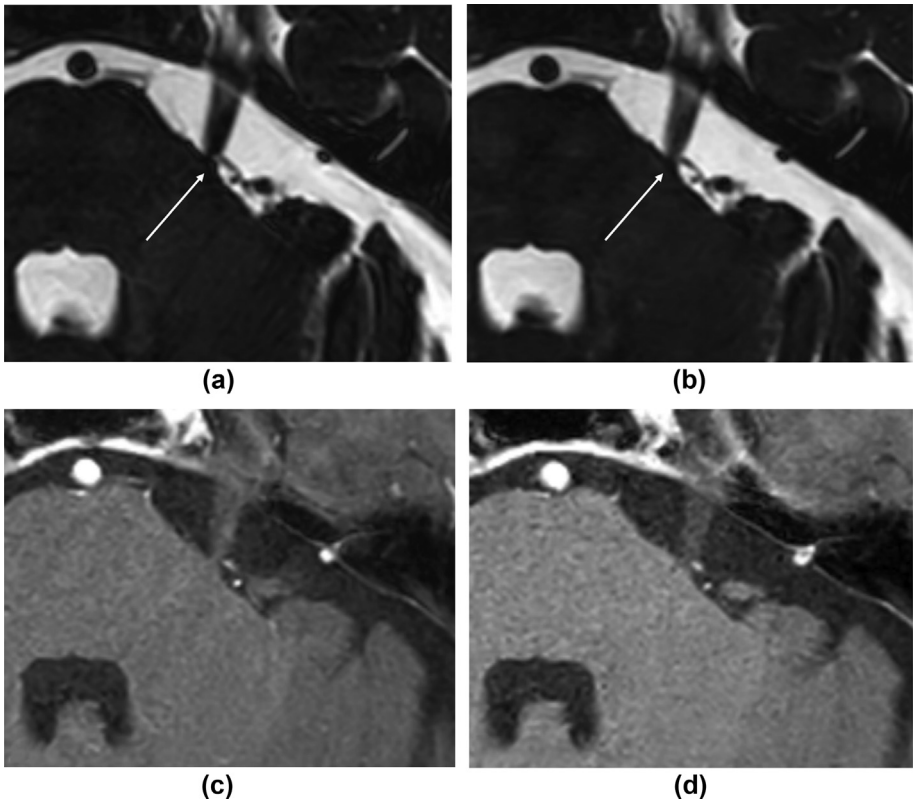

Figure 1 Axial T2 VISTA (top, a and b) and CE 3D T1 TFE (bottom, c and d) images were obtained from an 80-year-old man with suspicion of trigeminal neuralgia and complaining of left facial pain. The left anterior inferior cerebellar artery directly contacted the root entry/exit zone of the left trigeminal nerve with indentation (thin arrows). The overall image quality and nerve and vessel discrimination were similar between SENSE (left: a and c) and CS-SENSE (right: b and d). Additionally, the imaging diagnoses of the two radiologists were neurovascular compression syndrome on both SENSE (left: a and c) and CS-SENSE (right: b and d).

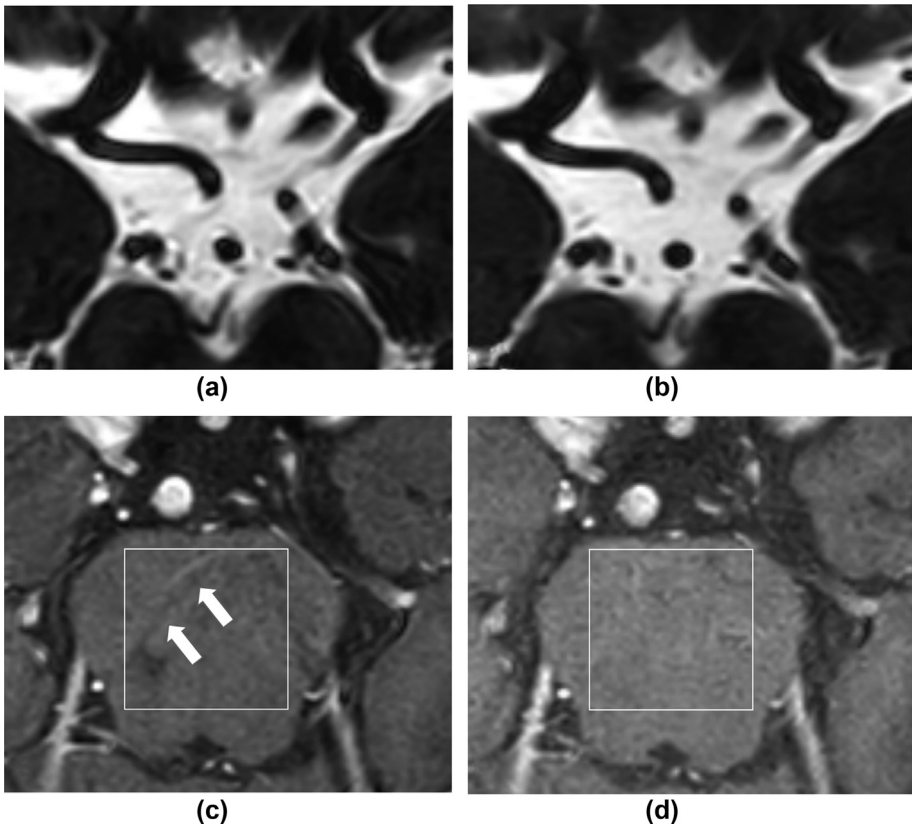

Figure 2 Images of a 43-year-old man with left hemifacial spasm (top, a and b) and a 68-year-old woman with left hemifacial spasm (bottom, c and d). On T2 VISTA, CSF homogeneities are superior on CS-SENSE (b) than on SENSE (a). On CE 3D T1 TFE, ghost artefacts (thick arrows), which are noticeable on CE 3D T1 TFE with SENSE (c) are not visible on CE 3D-T1 TFE with CS-SENSE (d). Additionally, the SNR is higher on CS-SENSE (c) than on SENSE (d) in CE 3D T1 TFE. The SNRs measured in a 2×2 cm region of interest in the mid pons (box) were 888 and 945.4 on SENSE and CS-SENSE, respectively.

imaging sequences of choice.[1,4–7] As the authors' institution uses T2 VISTA and CE 3D T1 TFE in the protocols for NVSC, these two sequences were evaluated in the present study, and the overall proportion of agreement between the two neuroradiologists for diagnosis of NVCS was 95%.

As a representative under-sampling technique, CS can reduce scan time by non-uniform sampling of k-space, with the sampling being denser in the centre than in the periphery.[12,13] As a result, these techniques have no choice but to show sparsity in the k-space data. Data under-sampling in a coherent (predictable) pattern creates discrete aliasing "ghost" artefacts that can wrap over the image. With the non-uniform sampling of CS, these artefacts are instead distributed as diffuse noise across the entire image, which can later be removed by wavelet transform and iterative reconstruction, so called "de-noising".[12,13,25] Furthermore, other qualitative and quantitative image parameters are preserved. Additionally, because the parallel and CS imaging techniques rely on different pieces of ancillary information for image reconstruction, it is possible to combine these two techniques for CS-SENSE imaging.[26,27] This combination of the two techniques is synergistic and results in an imaging-acceleration factor that exceeds the accelerations achieved by either parallel imaging or CS alone, while still keeping image noise low.[18,27] Liang *et al.* illustrated this principle using MRI phantoms, demonstrating the superior performance of CS-SENSE relative to parallel imaging or CS alone at a range of increased acceleration factors.[27] A few studies have evaluated the performance of CS-SENSE imaging of the brain in a clinical patient population.[14,18] Vranic *et al.* evaluated the clinical performance of CS-SENSE 3D fluid attenuation inversion recovery (FLAIR) and 3D T1WI in a brain tumour population and demonstrated that CS-SENSE reduced scan time without sacrificing image quality.[18] In contrast to the previous study, the present study evaluated the clinical performance of CS-SENSE for both 3D T2WI and CE-T1WI with an HR (acquisition voxel size: 0.5×0.5×1.2 mm) acquisition that has not been evaluated previously with acceleration techniques. CS-SENSE provided significant reductions in scan time compared with SENSE, without significant differences in overall image quality, vessel discrimination, and nerve discrimination between SENSE and CS-SENSE. These results suggest that CS-SENSE can reduce the scan time of both HR-3D T2WI and CE-T1WI without sacrificing image quality or clinical performance. Additionally, CS-SENSE was significantly superior to SENSE in terms of CSF homogeneity on T2 VISTA and the existence of ghost artefact on CE 3D T1 TFE, thereby demonstrating the

additional value of the de-noising effect on the clinical performance of both HR-3D T2WI and CE-T1WI.

In this study, the SNR $_{\text{pontine parenchyma}}$ on CE 3D T1 TFE was significantly higher with CS-SENSE than with SENSE; however, a direct comparison of SNR between CS-SENSE and SENSE is inadequate because SNR is a valid parameter within the fixed voxel dimensions; the definition of SNR does not have equal meanings between CS-SENSE and SENSE (parallel imaging).[13] In addition, the SNR can be increased by artefacts due to sparse sampling, and can be decreased by regularisation of artefact and de-noising.[28,29] Therefore, a specific focus on a direct comparison of SNR between SENSE and CS-SENSE is not meaningful. It is known that the SNR is degraded with increases in acceleration factor.[13] Therefore, further specific studies for optimisation of the SNR of cranial nerve MRI for NVCS are recommended.

There were several limitations to this study. First, only HR CE-T1WI and T2WI for cranial nerves were evaluated, and other sequences including FLAIR and FLAIR with enhancement also require investigation. A further study with various sequence of MRI will be needed. Second, only one CS-SENSE acceleration factor was evaluated in both CE-T1WI and T2WI. Although this factor was regarded as optimal in the authors' centre, different acceleration factors need to be assessed.

In conclusion, CS-SENSE appears to be superior to SENSE for reducing motion artefact and the scan time of HR-3D T2 VISTA T2WI and CE-3D T1 TFE sequences in patients with suspected NVCS, without a loss of overall image quality. On the basis of these results, the use of CS-SENSE in clinical practice can be considered to reduce the scan time of HR cranial nerve MRI protocols, without a loss of image quality.

Disclosures of conflicts of interest

The authors declare no conflict of interest.

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