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Hybrid of Compressed Sensing and Parallel Imaging Applied to Three-dimensional Isotropic T$_2$-weighted Turbo Spin-echo MR Imaging of the Lumbar Spine

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Purpose: The hybrid compressed sensing (hybrid-CS) technique can shorten the acquisition time compared with the sensitivity encoding (SENSE) technique in lumbar MRI. To evaluate the feasibility of a hybrid-CS technique in comparison with 3D isotropic T$_2$-weighted turbo spin-echo (3D volume isotropic turbo spin-echo acquisition [VISTA]) MRI of the lumbar spine.

Materials and Methods: The Institutional Review Board approved this study and informed consent was obtained from participants prior to study entry. Sixteen healthy volunteers underwent lumbar spine 3D VISTA with conventional parallel imaging for SENSE and hybrid-CS at 3T. We recorded the image acquisition times of SENSE and hybrid-CS. We compared the signal-to-noise ratio (SNR) in spine, cerebrospinal fluid (CSF), lumbar disc, epidural fat, and erector spinae muscle, and the contrast of spine, CSF, and disc, and performed qualitative image analysis assessment, between the two image sequences.

Results: The image acquisition time for hybrid-CS was 39.2% shorter than that of SENSE (218.4/358.8 s). The contrast of CSF and SNR of the spine was significantly higher with hybrid-CS than with SENSE ($P < 0.05$). The SNR of the disc and muscle was significantly higher with SENSE than with hybrid-CS ($P < 0.05$). There were no significant differences in the contrast of spine, disc, and fat, and SNR of CSF and fat between hybrid-CS and SENSE. There were no significant differences in the qualitative evaluation between hybrid-CS and SENSE.

Conclusion: Compared with SENSE, hybrid-CS for 3D VISTA can shorten image acquisition time without sacrificing image quality.

Keywords: *hybrid compressed sensing, three-dimensional isotropic T$_2$-weighted turbo spin-echo, sensitivity encoding, lumbar spine*

Introduction

Lumbar spinal imaging, especially soft tissue and spinal nerve evaluation, is usually performed with MRI.[1] 3D MRI can be used to acquire detailed morphologic data.[2] By using this technique, high spatial resolution multiplanar reconstruction images with a high signal-to-noise ratio (SNR) were made. Previous reports have suggested that this technique is useful for the evaluation of lumbar disc herniation and lumbar stenosis.[3,4] However, this technique has the disadvantage of a long scan time, which can be problematic in patients with low back pain.

To reduce the scan time, a parallel imaging technique called sensitivity encoding (SENSE) was introduced. However, it is usually associated with a drop in the SNR, attributed to an increase in the acceleration factor or the geometry factor.[5] Several undersampling methods have been introduced,[6,7] which can reduce scan time but have the disadvantages of streak artifacts, image noise, and reduced image quality. If *k*-space is uniformly undersampled, artifact containing a low-frequency component will arise. Similarly, random sampling methods yield noise-like artifact.

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The compressed sensing (CS) technique was introduced to overcome these disadvantages.[8,9] The CS technique consists of random undersampling and image reconstruction that is tuned for sparse data,[10] where "sparse data" means that there are relatively few significant pixels with nonzero values. For example, angiograms are extremely sparse in pixel representation. Previous reports mainly evaluated the usefulness of CS technique for reducing the scan time preserving image quality in sparse data such as magnetic resonance choledochopancreatography (MRCP) and brain MR angiography.[11,12]

However, most MR images are not sparse in general—most of the pixels in an MR image are not black, but contain many levels of the grayscale. Therefore, CS is not widely used for routine examinations. To solve this problem, some studies reported the feasibility of the combination use of CS and SENSE for clinical turbo spin-echo (TSE) sequences such as 3D knee examinations.[13] A hybrid technique combining CS and SENSE (hybrid-CS) was introduced for clinical examination with a variable density compressive sampling that automatically optimizes the balance between random basis and SENSE basis sampling for each examination. To the best of our knowledge, there have been no previous reports about the usefulness of the hybrid-CS technique compared with SENSE in lumbar spine imaging. Lumbar images contain high-contrast objects (fat and cerebrospinal fluid [CSF]) and the low-contrast objects (spinal and muscle). We hypothesized that the hybrid-CS technique will reduce the scan time compared with the SENSE technique, while preserving the quality of the 3D lumbar images.

The aim of this study was to evaluate the feasibility of a hybrid CS technique for 3D isotropic T_2-weighted TSE sequence of the lumbar spine.

Materials and Methods

The Institutional Review Board approved this study and informed consent was obtained from participants prior to study entry.

Population
Magnetic resonance imaging was performed on the lumbar spine of 16 healthy volunteers (14 men and 2 women; age range 25–51 years; mean age 34.4 ± 8.0 years, weight range 48–98; mean weight 66.9 ± 13.4 kg, height range 158–181 cm; mean height 169.5 ± 6.6 cm). All images were acquired in December 2017. All volunteers had not undergone surgery.

MRI sequence and parameters
We performed lumbar spine studies on a 3T MRI scanner (Ingenia CX, R5.4; Philips Medical Systems, Eindhoven, The Netherlands) with a 32-element phased-array Direct Digital radio-frequency (RF) receiver coil and spine coil. After scout images, we scanned 3D isotropic T_2-weighted TSE (3D VISTA) of the lumbar spine with conventional parallel imaging (SENSE, acceleration factor = 2), which are the

parameters recommended by the MRI vendor. We also scanned 3D VISTA imaging of the lumbar spine with hybrid-CS (compressed SENSE, acceleration factor = 8, average = 2) with the goal of decreasing scan time by 50%. We tried to replicate the study parameters for the two sequences as much as possible. A detailed MRI protocol can be found in Table 1.

Quantitative image analysis
A board-certified radiologist with 15 years of experience with MRI performed quantitative image analysis on source images. We selected representative slice levels that depicted the center of the spine, CSF, disc, fat, and muscle in each subject. Signal intensity (SI) was measured by placing circular ROIs on each tissue (Fig. 1). ROIs were at least 60 mm^2, and were placed in homogeneous, artifact-free areas of each tissue. Image noise was defined as the standard deviation (SD) of the same ROIs for SI because the background noise was too low. We calculated the SNR and contrast for 3D VISTA with the parallel acquisition technique.

The SNR of the spine, CSF, disc, fat, and spinal muscle was calculated with the following formula [1]:

$$SNR = \frac{mean\ SI}{mean\ SD} \qquad [1]$$

The contrast between each pair of tissues (spine, CSF, disc, and fat) and muscle was evaluated with the formula [2]:

$$Contrast\ ratio = \frac{mean\ SI\ of\ issue}{mean\ SI\ muscle} \qquad [2]$$

Table 1 Scan parameters

	SENSE	Hybrid-CS
TR (ms)	1300	1300
TE (ms)	182	182
FOV (mm)	280	280
Matrix	288 × 576	288 × 576
Acquisition voxel (mm)	0.97/0.97/1.00	0.97/0.97/1.00
Reconstruction voxel (mm)	0.49/0.49/0.50	0.49/0.49/0.50
Stacks	180	180
Acquisition slice thickness (mm)	1	1
Reconstruction slice thickness (mm)	0.5	0.5
Total scan duration (s)	358.8	218.4
Turbo factor	80	80
Echo space (ms)	5.4	5.6
Band width (Hz/pixel)	384.1	384.1
SENSE reduction factor	P2/S1	None
CS-SENSE reduction factor	None	8
Slice orientation	Coronal	Coronal

SENSE, sensitivity encoding; CS, compressed sensing.
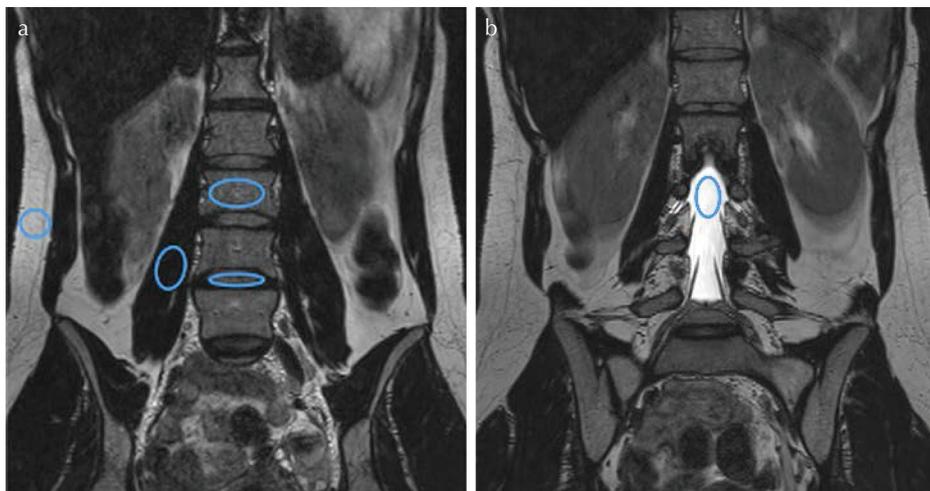
Fig. 1 (**a** and **b**) show ROIs (circle) of CSF, disc, fat, and spine for SENSE and hybrid-CS images. SENSE, sensitivity encoding; CS, compressed sensing; CSF, cerebrospinal fluid.

Qualitative image analysis

The lumbar spine images were randomly assigned the numbers from 1 to 32 by computer software (Microsoft Excel, Microsoft Japan, Tokyo, Japan). The radiologists then reviewed the images without knowledge of the individual subject's characteristics and acquisition parameters. All images were qualitatively assessed by two radiologists with more than 15 years of experience (15 and 21 years, respectively) evaluating MRI images. They were blinded to the acquisition techniques used. Overall image quality, sharpness, and contrast of the spine, CSF, disc, fat, and muscle were scored on a four-point scale (1 = poor; 2 = fair; 3 = good; 4 = excellent). Blurring and motion artifacts resulting from respiration were also scored as follows: 1 = image not diagnostic because of artifacts; 2 = major artifacts without diagnostic relevance; 3 = minor artifacts; 4 = no artifacts. In cases of inter-observer disagreement, final decisions were reached by consensus.

Statistical analysis

All numerical values were reported as the mean ± SD. We used a paired t-test to compare the image acquisition time, SNR, and contrast level with the SENSE and hybrid-CS techniques. The Wilcoxon signed rank test was used for qualitative analysis. We used the following interpretation of the kappa coefficients: <0.20 = slight, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = good, and 0.81–1.00 = excellent. Values of $P < 0.05$ were considered statistically significant. We used an open-source statistical software package for statistical analyses (software R version 3.4.1, The R Foundation for Statistical Computing, Vienna, Austria).

Results

All lumbar spine studies were completed successfully. Quantitative and qualitative data are shown in Tables 2 and 3. The image acquisition time was 39.2% shorter with the hybrid-CS than SENSE (218.4 s/358.8 s) (Table 2).

Table 2 Quantitative image analysis

	Location	SENSE	Hybrid-CS	P
SNR	Spine	5.6 ± 1.3	6.4 ± 1.4	<0.05
	CSF	23.5 ± 10.8	21.1 ± 5.8	0.25
	Disc	5.9 ± 2.0	5.1 ± 1.7	<0.05
	Fat	24.4 ± 4.9	23.2 ± 5.0	0.32
	Muscle	2.4 ± 0.4	2.1 ± 0.3	<0.05
Contrast	Spine	6.1 ± 1.9	6.8 ± 1.8	0.21
	CSF	62.9 ± 16.3	76.3 ± 15.1	<0.01
	Disc	4.9 ± 1.9	4.9 ± 1.7	0.62
	Fat	14.6 ± 3.4	15.6 ± 3.1	0.30

Data are the mean ± standard deviation; SNR, signal-to-noise ratio; SENSE, sensitivity encoding; CSF, cerebrospinal fluid.

Table 3 Qualitative image analysis (consensus)

Variable	SENSE	Hybrid-CS	P
Image noise	3.8 ± 0.4	3.6 ± 0.5	0.18
Image contrast	3.8 ± 0.4	3.8 ± 0.4	1.0
Image sharpness	3.2 ± 0.4	3.6 ± 0.6	0.06
Artifact	3.9 ± 0.3	3.8 ± 0.4	0.16
Overall image quality	3.9 ± 0.3	3.9 ± 0.3	0.32

Data are the mean ± standard deviation. CS, compressed sensing; SENSE, sensitivity encoding.

Quantitative image analysis

Signal-to-noise ratio of the spine was significantly higher with hybrid-CS than with the SENSE technique (6.4 ± 1.4 vs. 5.6 ± 1.3, $P < 0.05$). SNR of the disc was significantly higher with the SENSE technique than with hybrid-CS (5.9 ± 2.0 vs. 5.1 ± 1.7, $P < 0.05$). SNR of the muscle was significantly higher with the SENSE technique than with hybrid-CS (2.4 ± 0.4 vs. 2.1 ± 0.3, $P < 0.05$). There were no significant

differences between SNR of the CSF and fat with the SENSE technique and hybrid-CS (CSF: 23.5 ± 10.8 vs. 21.1 ± 5.8, $P = 0.25$, fat: 24.4 ± 4.9 vs. 23.2 ± 5.0, $P = 0.32$). The change in the SNR from SENSE to hybrid-CS varied from −13.6% to 14.3% (spine: 14.3%, CSF: −10.3%, disc: −13.6%, fat: −5.0% and muscle: −12.5%).

Contrast of the CSF with hybrid-CS was higher than that of the SENSE technique (76.3 ± 15.1 vs. 62.9 ± 16.3, $P < 0.01$). There were no significant differences between contrast of the spine, disc, and fat with hybrid-CS and SENSE (spine: 6.1 ± 1.9 vs. 6.8 ± 1.8, $P = 0.21$, disc: 4.9 ± 1.9 vs. 4.9 ± 1.7, $P = 0.62$, fat: 14.6 ± 3.4 vs. 15.6 ± 3.1, $P = 0.30$). The change in the contrast from SENSE to hybrid-CS varied from −10.3% to 21.3% (spine: −10.3%, CSF: 21.3%, disc: 0% and fat: −6.4%).

The results of quantitative image analysis are shown in Figs. 2 and 3.

Qualitative image analysis

There were no significant differences in qualitative analysis in contrast, sharpness, noise and artifact, or overall image quality between the SENSE and the hybrid-CS techniques ($P > 0.05$). There was moderate-to-substantial inter-observer agreement with respect to overall image quality, contrast, sharpness, noise, and artifact.

Representative cases are shown in Figs. 4 and 5.

Discussion

Our results demonstrated that hybrid-CS can reduce scan time without sacrificing image quality for the generation of isotropic 3D VISTA lumbar MR images. There were small changes in SNR (−13.6% to 14.3%) and image contrast (−10.3% to 21.3%); however, there were no significant differences in qualitative analysis between SENSE and hybrid-CS.
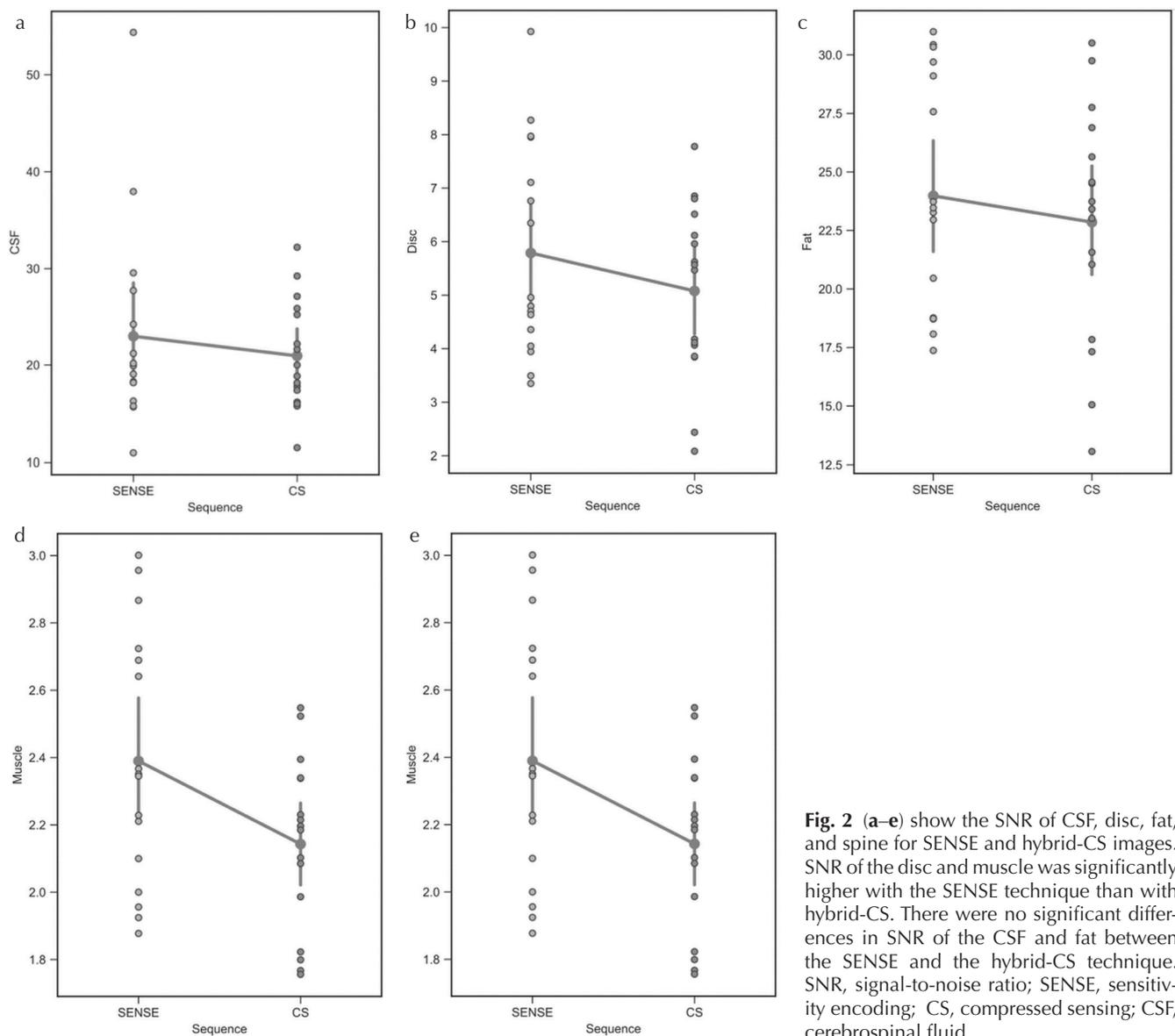
Fig. 2 (**a**–**e**) show the SNR of CSF, disc, fat, and spine for SENSE and hybrid-CS images. SNR of the disc and muscle was significantly higher with the SENSE technique than with hybrid-CS. There were no significant differences in SNR of the CSF and fat between the SENSE and the hybrid-CS technique. SNR, signal-to-noise ratio; SENSE, sensitivity encoding; CS, compressed sensing; CSF, cerebrospinal fluid.
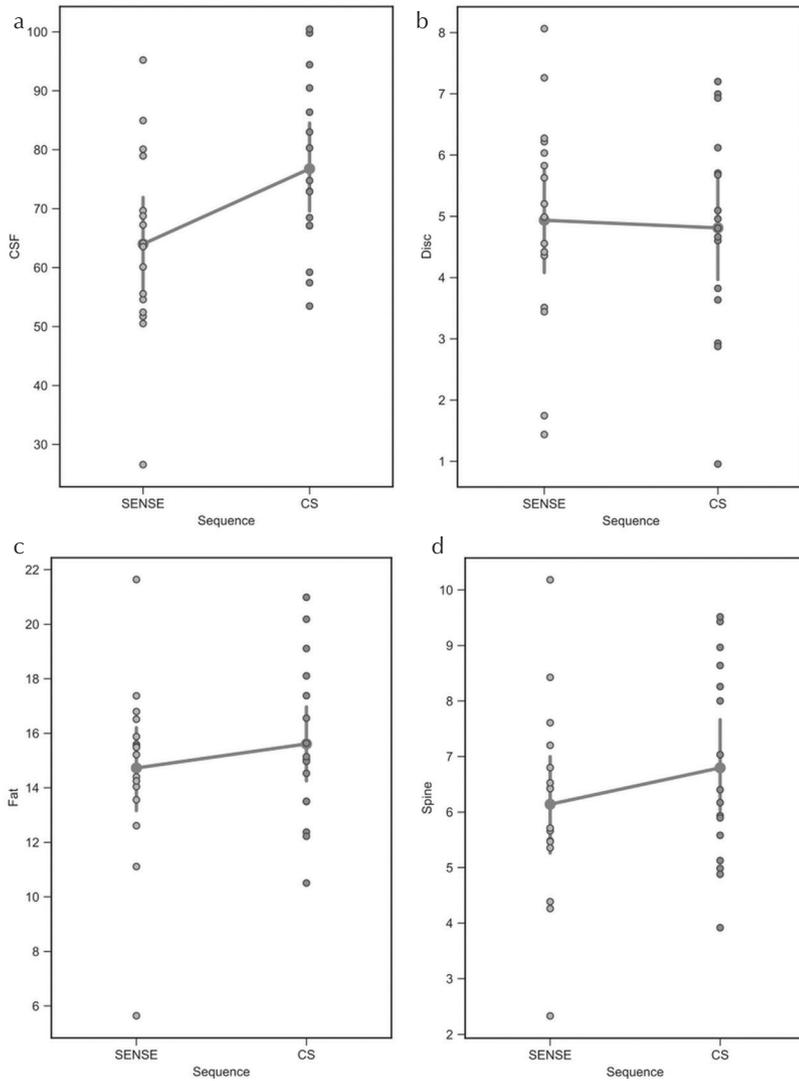
Fig. 3 (**a**–**d**) show the contrast of CSF, disc, fat, muscle and spine. SNR of the spine was significantly higher with the hybrid-CS technique than that of the SENSE technique. Contrast of the CSF with the hybrid-CS was higher than that of the SENSE. There were no significant differences in contrast of the spine, disc, and fat between hybrid-CS and SENSE. SNR, signal-to-noise ratio; SENSE, sensitivity encoding; CS, compressed sensing; CSF, cerebrospinal fluid.
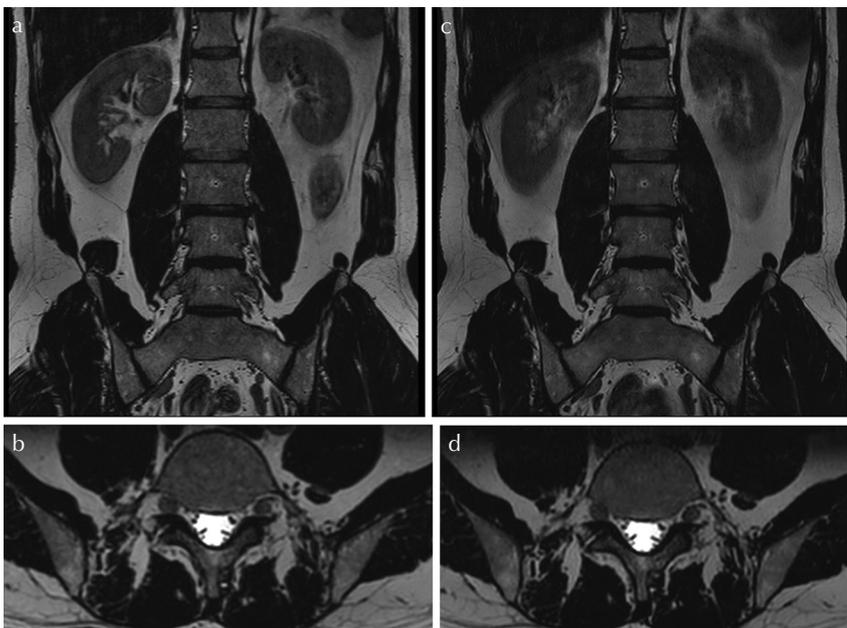
Fig. 4 A 32-year-old volunteer was imaged with 3D VISTA with SENSE and hybrid-CS. We show his coronal and axial images of SENSE (**a** and **b**) and hybrid-CS (**c** and **d**). The image quality of SENSE and hybrid-CS are almost the same. SENSE, sensitivity encoding; CS, compressed sensing; 3D-VISTA, three-dimensional isotropic T_2-weighted fast spin-echo.
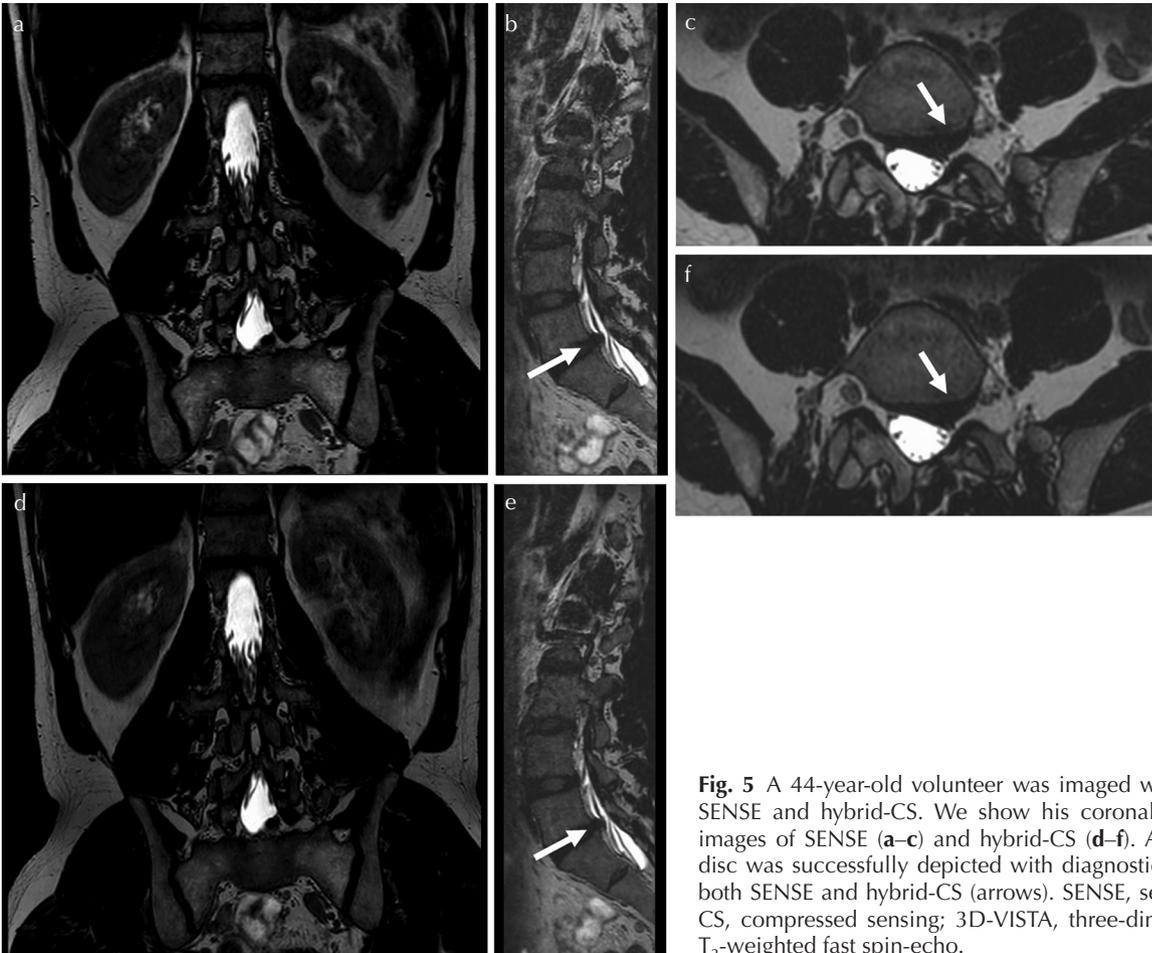
Fig. 5 A 44-year-old volunteer was imaged with 3D-VISTA with SENSE and hybrid-CS. We show his coronal sagittal and axial images of SENSE (**a**–**c**) and hybrid-CS (**d**–**f**). A lumbar herniated disc was successfully depicted with diagnostic image quality for both SENSE and hybrid-CS (arrows). SENSE, sensitivity encoding; CS, compressed sensing; 3D-VISTA, three-dimensional isotropic T_2-weighted fast spin-echo.

Compressed sensing is an acceleration technique for recovering an unknown sparse signal from a small number of linear measurements. Images with a sparse representation can be recovered from randomly undersampled *k*-space data. The sparsity means the MR image exploited to significantly undersampled *k*-space. The sequence of compressed sensing reconstruction was as follows[14]: (1) Random undersampling was performed from *k*-space data; (2) the image was created from the undersampling data from *k*-space using the inverse Fourier transform; (3) sparse data were created from the image using the wavelet transform; (4) a nonlinear thresholding scheme can recover the sparse coefficients, effectively recovering the image itself and remove the noise-like aliasing; (5) optimized sparse data were transformed to the image and the sparsifying transform was repeated. Several iterative reconstruction schemes (3–5) were performed and removed the image noise.

Parallel imaging techniques such as SENSE are acceleration techniques using multiple phase array coils.[15] This technique has the disadvantage of yielding aliasing artifact and decreasing the SNR for the high acceleration factors. Hybrid-CS technique can overcome the disadvantages of SENSE.

In this study, we used the new hybrid-CS technique (SENSE-based compressed SENSE). Basically, the function of the hybrid CS technique is parallel imaging, but a more flexible and sophisticated sampling algorithm is applied automatically. The hybrid-CS technique theoretically does not require additional acquisition of auto-calibration lines wherein non-SENSE-based CS techniques are often required. Such additional acquisition results in loss of the sampling scheme flexibility. Furthermore, such non-SENSE-based CS techniques reduce SNR and CNR and increase image blurring compared with those with conventional imaging. In the hybrid-CS technique, the SENSE-based balanced sampling pattern is automatically optimized using a variable density incoherently undersampled scheme that samples the center of the *k*-space more densely than the periphery. The sampling schemes also automatically minimize other sources of artifacts, such as eddy currents and patient motion. For reconstruction, automatic derivation of the wavelength threshold is applied for faster and robust reconstruction.

Hybrid CS was effective in high-contrast areas, so it was applied to MRA, the cine-image sequences of cardiac MRI, and MRCP.[8,12,16] The contrast and SNR of CSF for hybrid-CS were significantly higher compared with those

for SENSE. However, contrast and SNR of muscle and fat for hybrid-CS were significantly lower compared with those for SENSE. In T$_2$-weighted fast spin-echo, CSF is high-contrast objects, and muscle and fat are low contrast-objects. In this study, the image quality using the hybrid-CS technique was almost same with that of SENSE. However, the SNR and contrast of high-contrast anatomies and low-contrast anatomies for hybrid-CS technique and SENSE were somewhat different.

We hypothesized that relatively heterogeneous and low-signal-intensity objects (such as muscle and fat) might be removed in sparse domains similar to artifact; therefore, the SNR of fat and muscle for hybrid CS might be lower compared with those for SENSE. However, the relatively homogenous and high-signal-intensity objects (such as CSF) might not be removed by the nonlinear thresholding scheme. Therefore, the SNR of CSF for hybrid CS might be higher compared with those for SENSE. A slight image difference between SENSE and hybrid CS technique might not affect the diagnostic performance.

Limitations

Our study has several limitations. First, this study is that this is a volunteer study that includes only young people. Including elderly patients who have difficulty in lying still might be desirable for evaluating the merit of short scan time of hybrid-CS. However, scanning two long sequences in these patients might be uncomfortable and increase the rate of poor study and it might result in impairing the rights of the patients. In addition, in this study period, the performance of hybrid-CS for spinal 3D TSE is uncertain. We have used this sequence as a routine examination of the lumbar spine because we confirmed the usefulness of hybrid-CS 3D VISTA in this study. Furthermore, obtaining approval from our Institutional Review Board for a comparable study of patients was difficult; therefore, we only estimated scan data of the volunteers in this study. Second, this preliminary study was designed to evaluate the feasibility of CS in shortening the scan time of 3D VISTA in the region of the lumbar spine, with only one acceleration factor; using other acceleration factors might change the results, i.e., scan time and SNR. Future work should evaluate which acceleration factor for CS is the most appropriate for clinical use. At last, we exclusively used a standard denoising level of 15%, which is recommended by the vendor, and we acknowledge that altering the denoising level or denoising methods may have affected the results of the present study.

Conclusion

CS for 3D VISTA can shorten image acquisition time without sacrificing image quality compared with SENSE sequence.

Conflicts of Interest

Masami Yoneyama is an employee of Philips Japan. The other authors declare no conflicts of interest in regard to the products under investigation or the subject matter discussed in this manuscript.

References

1. Maravilla KR, Lesh P, Weinreb JC, Selby DK, Mooney V. Magnetic resonance imaging of the lumbar spine with CT correlation. AJNR Am J Neuroradiol 1985; 6:237–245.
2. Eberhardt KE, Hollenbach HP, Huk WJ. [3D-MR myelography in diagnosis of lumbar spinal nerve root compression syndromes. Comparative study with conventional myelography]. Aktuelle Radiol 1994; 4:313–317. (in German)
3. Lee S, Jee WH, Jung JY, Lee SY, Ryu KS, Ha KY. MRI of the lumbar spine: comparison of 3D isotropic turbo spin-echo SPACE sequence versus conventional 2D sequences at 3.0 T. Acta Radiol 2015; 56:174–181.
4. Blizzard DJ, Haims AH, Lischuk AW, Arunakul R, Hustedt JW, Grauer JN. 3D-FSE isotropic MRI of the lumbar spine: novel application of an existing technology. J Spinal Disor Technol 2015; 28:152–157.
5. Ham CL, Engels JM, van de Wiel GT, Machielsen A. Peripheral nerve stimulation during MRI: effects of high gradient amplitudes and switching rates. J Magn Reson Imaging 1997; 7:933–937.
6. Spiniak J, Guesalaga A, Mir R, Guarini M, Irarrazaval P. Undersampling *k*-space using fast progressive 3D trajectories. Magn Reson Med 2005; 54:886–892.
7. Jones RA, Haraldseth O, Müller TB, Rinck PA, Oksendal AN. *K*-space substitution: a novel dynamic imaging technique. Magn Reson Med 1993; 29:830–834.
8. Zhou R, Huang W, Yang Y, et al. Simple motion correction strategy reduces respiratory-induced motion artifacts for k-t accelerated and compressed-sensing cardiovascular magnetic resonance perfusion imaging. J Cardiovasc Magn Reson 2018; 20:6.
9. Li S, Zhu Y, Xie Y, Gao S. Dynamic magnetic resonance imaging method based on golden-ratio cartesian sampling and compressed sensing. PloS One 2018; 13:e0191569.
10. Lustig M, Donoho D, Pauly JM. Sparse MRI: the application of compressed sensing for rapid MR imaging. Magn Reson Med 2007; 58:1182–1195.
11. Zhu L, Wu X, Sun Z, et al. Compressed-sensing accelerated 3-dimensional magnetic resonance cholangiopancreatography: application in suspected pancreatic diseases. Invest Radiol 2018; 53:150–157.
12. Yamamoto T, Okada T, Fushimi Y, et al. Magnetic resonance angiography with compressed sensing: an evaluation of moyamoya disease. PloS One 2018; 13:e0189493.
13. Lee SH, Lee YH, Suh JS. Accelerating knee MR imaging: compressed sensing in isotropic three-dimensional fast spin-echo sequence. Magn Reson Imaging 2018; 46:90–97.

14. Kustner T, Wurslin C, Gatidis S, et al. MR image reconstruction using a combination of compressed sensing and partial fourier acquisition: ESPReSSo. IEEE Trans Med imaging 2016; 35:2447–2458.
15. Hamilton J, Franson D, Seiberlich N. Recent advances in parallel imaging for MRI. Prog Nucl Magn Reson Spectrosc 2017; 101:71–95.
16. Kwon H, Reid S, Kim D, Lee S, Cho J, Oh J. Diagnosing common bile duct obstruction: comparison of image quality and diagnostic performance of three-dimensional magnetic resonance cholangiopancreatography with and without compressed sensing. Abdom Radiol (NY) 2018; 43:2255–2261.