Accelerated 3D T2-Weighted SPACE Using Compressed Sensing for Paediatric Brain Imaging

Hyun Gi Kim (catharina@catholic.ac.kr)
The Catholic University of Korea
Se Won Oh
The Catholic University of Korea
Dongyeob Han
Siemens Healthineers Ltd
Jee Young Kim
The Catholic University of Korea
Gye Yeon Lim
The Catholic University of Korea

Research Article

Keywords: Accelerated, SPACE, paediatric, brain imaging

Posted Date: August 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-754283/v1

Abstract

The purpose of this study was to compare the image quality of the single-slab, 3D T2-weighted turbo-spin-eco sequence with high sampling efficiency (SPACE) with accelerated SPACE using compressed sensing (CS-SPACE) in paediatric brain imaging. A total of 116 brain MRI (53 in SPACE group and 63 in CS-SPACE group) were obtained from children aged 16 years old or younger. Quantitative image quality was evaluated using the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). The sequences were qualitatively evaluated for overall image quality, SNR, general artifact, cerebrospinal fluid (CSF)-related artifact and grey-white matter differentiation. The two sequences were compared for the total and for two age groups (< 24 months vs. ≥ 24 months). CS application in 3D T2-weighted imaging resulted in 8.5% reduction in scanning time. Quantitative image quality analysis showed higher SNR (Median [Interquartile range]; 29 [25] vs. 23 [14], $P = .005$) and CNR (0.231 [0.121] vs. 0.165 [0.120], $P = .027$) with CS-SPACE compared to SPACE. Qualitative image quality analysis showed better image quality with CS-SPACE for general artifact ($P = .024$) and CSF-related artifact ($P < .001$). CSF-related artifacts reduction was more prominent in the older age group (≥ 24 months). Overall image quality ($P = .162$), SNR ($P = .726$), and grey-white matter differentiation ($P = .397$) were comparable between SPACE and CS-SPACE. In conclusion, compressed sensing applied 3D T2-weighted images showed comparable or superior image quality compared to conventional images with reduced acquisition time for paediatric brain.

Introduction

High-resolution three-dimensional (3D) imaging is now feasible in paediatric neuroimaging[1]. 3D imaging has advantages over 2D imaging as the reconstruction of different orientations can be done without additional scanning. In addition, volumetric assessment is more reliable with 3D imaging. One popular 3D imaging sequence for paediatric neuroimaging is the magnetization-prepared rapid gradient echo (MPRAGE) sequence, which generates T1-weighted images (T1WI)[1]. Compared to 3D T1WI, 3D T2-weigthed images (T2WI) are generally not applied to clinical practice. This is mainly because they require longer scanning times and result in lower contrast compared to 2D sequences. Still, 3D T2WI are being increasingly used for the quantification of brain structures[2–4].

Acceleration methods are important for paediatric magnetic resonance imaging (MRI) because they reduce the need for sedation and its consequent adverse effects while lowering the chance of movement by reducing scanning time. Several techniques have been introduced to reduce scanning time in children including compressed sensing[5,6], parallel imaging[7], simultaneous multisection imaging[8], radial k-space sampling[9], and artificial intelligence–based reconstruction[10]. Compressed sensing (CS) is the one of the most recently developed techniques[5,6] and has already been applied to adult neuroimaging studies[11–14].

When CS was used for head and neck magnetic resonance angiography, fast diagnostic-quality time-of-flight imaging was possible for the head and neck vessels[11,12]. In patients with multiple sclerosis, brain imaging times were 27% faster with similar diagnostic performance when CS was used for T2-weighted 3D fluid attenuated inversion recovery (FLAIR)[12]. CS achieves accelerated acquisition through non-linear iterative reconstruction of undersampled k-space data[6]. Although acceleration times depend on the acceleration factor, it is difficult to predict how much acceleration is realistically possible without significant degradation of image quality.

To the best of our knowledge, there has been no study regarding the clinical utility of CS when applied to 3D T2-weighted brain imaging in children. Children neuroimaging application can be different from adults, since they have different condition during scanning as well as different brain tissue contrast that is affected by development. Therefore, the purpose of our study was to compare the image quality of conventional 3D T2WI with that of 3D CS-applied T2WI in children.

Methods

This retrospective study was approved by our institutional review board (The Catholic University of Korea Catholic Medical Center) and the requirement for patient consent was waived. All experiments in this study were performed in accordance with relevant guidelines and regulations.

Patients

We reviewed the brain MR imaging of children (16 years or under) obtained from May 2019 to February 2020 using a 3T scanner (Vida; Siemens, Erlangen, German). We included brain MR imaging obtained between May 2019 and October 2019 using the conventional 3D T2-weighted turbo-spin-eco sequence with high sampling efficiency (SPACE) and brain MR imaging obtained between November 2019 and February 2020 using accelerated SPACE with compressed sensing (CS-SPACE). Demographic information was collected through a review of medical records. Patients were grouped according to sequence (SPACE vs. CS-SPACE) and age (younger than 24 months vs. 24 months or older).

Image acquisition

Scan parameters are described in detail in Table 1. All scans were acquired using 3T MRI with a 64-channel head coil. The spatial resolution of SPACE and CS-SPACE were the same (matrix, 320×320×208; FOV, 256×256×166.4 mm^3; voxel size, 0.4×0.4×0.8 mm^3). Repetition time was longer for CS-SPACE compared to SPACE (5000 msec vs. 3500 msec). SPACE was obtained using the CAIPIRINHA method with an acceleration factor of 4. For CS-SPACE, an acceleration factor of 7 was applied. The total scanning time for CS-SPACE was 193 s and for SPACE was 211 s, resulting in an 8.5% reduction in scanning time when CS was applied.

For scanning, neonates were fed, wrapped, and placed in a MedVac infant immobilizer (CFI Medical, USA). The need for sedation was determined by physicians and when patients had to be sedated for scanning, oral chloral hydrate (0.5–1 mL/kg) was the first choice of sedation and when patients could not be sedated with oral chloral hydrate, intravenous midazolam (0.025–0.05 mg/kg) was used. Since the number of sedated patients in each group could affect the nature of the artifacts observed, we compared the number of patients who were sedated between the CS-SPACE and SPACE groups.

Table 1
Parameters of SPACE and CS-SPACE

	SPACE	CS-SPACE
Echo time (msec)	502	450
Repetition time (msec)	3500	5000
Flip angle	Variable	Variable
Matrix	320×320×208	320×320×208
Field of view (mm^3)	256×256×166.4	256×256×166.4
Voxel size (mm^3)	0.8×0.8×0.8	0.8×0.8×0.8
Acceleration factor	4	7
Turbo factor	290	230
Echo spacing (msec)	3.72	3.72
Echo train duration (msec)	1045	859
Scan time (s)	211	193

Image quality evaluation

For quantitative analysis, regions of interests (ROIs) were manually drawn at the frontal white matter and deep grey matter. The ROIs were drawn using the Picture Archiving and Communication System (PACS) (TaeYoung Soft, Gyeonggi-do, Republic of Korea). The contrast-to-noise ratio (CNR) between white and grey matter was measured using the Michelson contrast equation. In this equation, the contrast is the difference between the maximal and minimal intensities divided by the sum of the maximal and minimal intensities[15]. The signal-to-noise ratio (SNR) was estimated as white matter intensities divided by the standard deviation of white matter[16]. Denoising effect of CS results in different effect on SNR and should be termed apparent SNR instead of SNR[6]. However, for the comparison with SPACE, this SNR estimation method was applied for CS-SPACE as well as SPACE. For interobserver agreement evaluation, two radiologists (with 10 years of experience in paediatric neuroradiology and with 13 years of experience in neuroradiology) drew ROIs. For interobserver agreement evaluation, one radiologist drew second ROIs after two weeks. The representative images for ROIs are in *Supplementary Fig. 1*.

For qualitative analysis, the two radiologists (one with 10 years of experience in paediatric neuroradiology [radiologist 1] and one with 13 years of experience in neuroradiology [radiologist 2]) performed visual assessments. MR images were analysed blindly and independently in random order. The sequences were qualitatively evaluated with 3-point scales for overall image quality, SNR, general artifacts, cerebrospinal fluid (CSF) -related artifacts, and grey-white matter differentiation. The grades for image quality, signal-to-noise ratio, and grey-white matter differentiation were defined as follows: 1 = poor, 2 = adequate, 3 = good. The grades for general and CSF-related artifacts were defined as follows: 1 = severe artifact, 2 = moderate artifact, 3 = mild or no artifact. For general artifacts, the degree of motion or truncation artifacts were evaluated[17]. For CSF-related artifacts, signal change and distortion inside and around the third ventricle were evaluated[18]. The representative images for image quality scales are in *Supplementary Fig. 2*.

Image quality was compared for the total study population and for each age group (younger than 24 months vs. 24 months or older). This approach was chosen because brain tissue contrast depends on myelination degree.

Statistical Analysis

Age and quantitative image quality values (CNR and SNR) were compared between SPACE and CS-SPACE using the Mann-Whitney test. Gender, use of sedation, and qualitative image analysis variables were compared between SPACE and CS-SPACE using either the Chi-square or Fisher's exact test. The mean values of the two radiologists' qualitative scales were compared between SPACE and CS-SPACE using Mann-Whitney test. Weighted Cohen's Kappa (κ) statistics were used to show interobserver agreement. Inter- and intraobserver agreements were defined as poor (0.00-0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (0.81-1.00). SPSS (version 27.0, IBM, Armonk, New York) were used for analysis and graphs were prepared using Graphpad prism software (version 8.4.2, San Diego, USA). P values < .05 were considered statistically significant.

Results

Patients

A total of 116 brain MRI scans were performed with either SPACE or CS-SPACE. Children underwent brain MR imaging for various indications, with prematurity, headaches, seizure, and trauma being the most common. There were 53 brain MRI scans obtained with the SPACE sequence and 63 scans obtained with the CS-SPACE sequence.

Demographic characteristics of the patients are summarized in Table 2. There was no significant difference in gender or age between the two sequences (P = .305). Sixty-two subjects underwent MR with sedation. For total patients, the use of sedation did not differ between CS-SPACE and SPACE (SPACE, 52.8% vs. CS-SPACE, 49.2%, P > .999). However, when the two age groups were compared, younger patients were more frequently sedated in the CS-SPACE group than the SPACE group (SPACE, 50.0% vs. CS-SPACE, 92.3%, P = .020). In older patients, the use of sedation did not differ between the two sequences (SPACE, 54.1% vs. CS-SPACE, 44.0%, P = .391).

Table 2
Demographic characteristics

	SPACE (n = 53)	CS-SPACE (n = 63)	*P* Value
Age (month)	76.1 ± 66.6	88.7 ± 64.5	.305
Age group			.333
< 24 months	16 (30.2%)	13 (20.6%)	
≥ 24 months	37 (69.8%)	50 (79.4%)	
Gender			> .999
Male	27 (50.9%)	31 (49.2%)	
Female	26 (49.1%)	32 (50.8%)	
Sedated subjects			
Total	28 (52.8%)	34 (49.2%)	> .999
< 24 months	8(50%)	12(92.3%)	.020
≥ 24 months	20(54.1%)	22(44%)	.391
Data – number (percentage)			

Quantitative image quality

Quantitative image quality of SPACE and CS-SPACE are summarized in Table 3 and Fig. 1. Regarding total subjects, both CNR (median [interquartile range]; 0.231 [0.121] vs. 0.165 [0.120], $P = .027$) and SNR (29 [25] vs. 23 [14], $P = .005$) were significantly higher with CS-SPACE than SPACE. When quantitative image quality was compared in patients under 24 months, SNR tended to be higher with CS-SPACE than SPACE (64 [49] vs. 36 [33], $P = .050$), but CNR showed no significant difference between the two sequences (0.088 [0.067] vs. 0.111 [0.097], $P = .630$). In patients 24 months and older, both CNR (0.242 [0.064] vs. 0.208 [0.115], $P = .048$) and SNR (27 [16] vs. 19 [8], $P < .001$) were significantly higher with CS-SPACE compared to SPACE.

Table 3
Quantitative image quality comparison between SPACE and CS-SPACE

	Total			**Age < 24 months**			**Age ≥ 24 months**		
Quantitative parameters	SPACE	CS-SPACE	*P* value	SPACE	CS-SPACE	*P* value	SPACE	CS-SPACE	*P* value
	(n = 53)	(n = 63)		(n = 16)	(n = 13)		(n = 37)	(n = 50)	
CNR	0.165 (0.120)	0.231 (0.121)	0.027	0.111 (0.097)	0.088 (0.067)	0.630	0.208 (0.115)	0.242 (0.064)	0.048
SNR	23 (14)	29 (25)	0.005	36 (33)	64 (49)	0.050	19 (8)	27 (16)	< 0.001
CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio									

Qualitative image quality

The qualitative image qualities of SPACE and CS-SPACE are summarized in Table 4 and Fig. 2. CSF-related artifacts between CS-SPACE and SPACE images were rated differently by both radiologists ($P < .001$). When mean scale values by the radiologists were compared, general artifact (3.0 [0.5] vs. 2.5 [0.5], $P = .024$) and CSF-related artifact (2.5 [0.5] vs. 2.0 [0.5] $P < .001$) showed higher values in CS-SPACE compared to SPACE. Overall image quality (SPACE vs. CS-SPACE; 2.0 [1.0] vs. 2.0 [0.5], $P = .162$), SNR (2.0 [0.5] vs. 2.5 [0.5], $P = .726$), and grey-white matter differentiation (2.5 [1.0] vs. 2.5 [0.5], $P = .397$) did not show significant differences.

In patients under 24 months, general artifacts were rated higher (radiologist 1, $P = .047$) or comparable (radiologist 2, $P = .426$) with CS-SPACE than SPACE. In patients 24 months or older, CSF-related artifacts were rated with higher scores with CS-SPACE than SPACE (both radiologists, $P < .001$). In patients under 24 months, CSF-related artifacts were not significantly different between the two images. Other qualitative features for image quality were comparable for SPACE and CS-SPACE in both age groups. Representative images of SPACE and CS-SPACE are shown in Fig. 3

Table 4
Qualitative image quality comparison between SPACE and CS-SPACE in age groups

	Total			**Age < 24 months**			**Age ≥ 24 months**		
Qualitative parameters	SPACE (n = 53)	CS-SPACE (n = 63)	*P* value	SPACE (n = 16)	CS-SPACE (n = 13)	*P* value	SPACE (n = 37)	CS-SPACE (n = 50)	*P* value
Overall image quality									
Radiologist 1	20/21/12	8/39/16	0.006	7/6/3	1/9/3	0.089	13/15/9	7/30/13	0.057
Radiologist 2	12/20/21	9/28/26	0.486	3/4/9	1/7/5	0.262	9/16/12	8/21/21	0.529
SNR									
Radiologist 1	9/29/15	9/39/15	0.736	4/8/4	4/8/1	0.471	5/21/11	5/31/14	0.840
Radiologist 2	9/22/22	5/30/28	0.325	2/7/7	0/8/5	0.348	7/15/15	5/22/23	0.489
Artifact									
Radiologist 1	8/14/31	2/16/45	0.064	2/6/8	0/1/12	0.047	6/8/23	2/15/33	0.131
Radiologist 2	4/13/36	2/8/53	0.118	1/3/12	0/1/12	0.426	3/10/24	2/7/41	0.191
CSF artifact									
Radiologist 1	21/23/9	3/37/23	< 0.001	3/6/7	0/8/5	0.188	18/17/2	3/29/18	< 0.001
Radiologist 2	9/29/15	0/25/38	< 0.001	0/4/12	0/4/9	0.811	9/25/3	0/21/29	< 0.001
GW differentiation									
Radiologist 1	3/33/17	2/40/21	0.805	3/9/4	2/10/1	0.415	0/24/13	0/30/20	0.811
Radiologist 2	0/19/34	0/33/30	0.110	0/6/10	0/8/5	0.360	0/13/24	0/25/25	0.245

Values are number of images assigned in 3-point scales (scale 1/2/3); SNR, signal-to-noise ratio; CSF, cerebrospinal fluid; GW, grey-white matter

Inter- and intraobserver agreements

Inter- and intraobserver agreements for SNR and CNR were good to excellent. Interobserver agreements κ for CNR and SNR were 0.856 (P< .001) and 0.610 (P< .001), respectively. Intraobserver agreements κ for CNR and SNR were 0.961 (P< .001) and 0.607 (P< .001), respectively. For qualitative image quality analysis, interobserver agreements were fair (0.261–0.393, P< .001).

Discussion

Our study showed that the application of CS to high-resolution 3D T2WI has the potential to reduce scanning times without degrading image quality in paediatric brain imaging. With CS, scanning times were reduced by 9% which resulted in higher or comparable image quality. Quantitative CNR and SNR were higher with CS-SPACE compared to SPACE, a difference that was more prominent in the older age group that had full myelination (i.e., ≥ 24 months in age). CSF-related artifacts decreased with CS-SPACE, and this reduction was also more prominent in the older age group.

Reducing scanning time is particularly important in paediatric MRI studies[19]. Sedation may be necessary for children to undergo MRI scanning and by reducing sedation time, we can reduce the potential risks of sedation such as cardiac and respiratory depression or neurologic damage in this vulnerable patient population[20]. Even if a child is cooperative enough to undergo MRI scanning without sedation, it is not easy for them to hold still for the entire examination and this presents another problem as patient motion during scanning leads to degraded image quality. To resolve the above issues, various acceleration techniques have been developed for faster MR studies such as parallel MRI, radial sampling, spiral sampling, and recently, CS[21]. CS generates images from random or pseudo-random undersampled k-space data using an iterative nonlinear method[21]. As this allows high temporal resolution, CS has been applied to cardiovascular and abdominal imaging in paediatric patients[21].

In this study, we applied CS to 3D volumetric T2-weighted brain imaging in children. Image quality improved using CS with 3D T2WI compared to conventional 3D T2WI and this was also observed in a previous study on adult brain imaging[22]. 3D volumetric imaging allows the retrospective analysis of brain structure along many axes which is an advantage over 2D images. It also allows quantitative imaging by enabling the calculation of cortical thickness or regional volume. For this reason, many research protocols for both paediatric and adult populations include 3D images rather than 2D images. In terms of T1WI, 3D imaging is considered to be the standard protocol for neonates, because it can identify more white matter punctate lesions that are frequently involved in neonates with ischemic insult[23]. In contrast, 3D T2WI imaging is not as well included in clinical practice, mainly because of its long scanning time. Nonetheless, T2WI is more suitable for anatomical segmentation[24] or for assessing myelination degree in young populations that have not reached full myelination[25]. We think that 3D T2WI could be more broadly applied to children by using CS to shorten acquisition time as well as improving image quality.

In contrast to previous studies that showed substantially reduced scanning times ranging from 20–70% using CS[12,26,27], our protocol resulted in approximately 9% reduction. This is mainly due to the longer TR set for CS-SPACE than conventional SPACE (5000 msec vs. 3500 msec). Further scan time reduction could be achieved with shorter repetition time; however, this reduction would be at the expense of image quality. Still, we achieved our initial goal to find an approach that could adapt 3D T2WI more reasonably to clinical settings since the scanning time of 2D T2-weighted spin echo imaging for paediatric brain MRI is approximately 2 min 30 seconds to 3 min 35 seconds and our scanning time was 3 min 13 seconds[15]. Further studies that discover ways to achieve additional time reduction are needed.

Interestingly, we found significant reduction of CSF-related artifacts after using CS-SPACE. CSF-related artifacts are categorized into time-of-flight effects and turbulent flow[18]. CSF-related artifacts at and around the third ventricle are explained with time-of-flight loss[18]. In a previous study that compared conventional and CS-applied 3D time-of-flight angiography, the use of CS resulted in better image quality[28]. Similar to this previous study, we postulate that the decrease in CSF-related artifacts is a result of undersampling and its reconstruction which leads to a denoising effect.

On the other hand, CS does not affect CSF-related artifacts identically when patients are of different ages and this is thought to be due to the different hemodynamic of CSF as younger patients show higher CSF velocities[29]. Unlike CSF-related artifacts, general artifacts decreased with the use of CS in the younger age group. We postulate that this is because of reductions in scanning time which may have led to less movement during scanning. Further scanning time reduction will result in less movement artifacts, but more study on this topic is necessary with a larger number of patients who are both sedated and not sedated.

There are several limitations to our study. Firstly, we compared the sequences in two different subjects for two different study periods. Secondly, there was large variation in age as we included patients with various degrees of brain maturation. As different results were found for each age group, large-scale studies that classify patients into more narrow age ranges could be needed. Thirdly, we did not evaluate specific artifacts that would be subject to the two sequences. A previous study applying CS to parallel imaging such as sensitivity encoding showed starry-sky or streaky-linear artifacts, which represented grainy image noise and horizontally oriented lines in the centre of the transverse reconstructed images, respectively[30].

In conclusion, the application of compressed sensing to high-resolution 3D T2-weighted imaging in children has reduced scanning times without degrading image quality. Both quantitative and qualitative image quality were comparable when 3D T2-weighted imaging with and without compressed sensing were compared. This advanced technique has potential to increase routine use of high-resolution 3D T2-weighted imaging in children’s brain.

Declarations

Author Contributions

H.G.K. conceived the idea. H.G.K and S.W.O. performed the acquisition and analysis of data. H.G.K and S.W.O. performed the interpretation of data. G.Y.L. supervised and reviewed the study. H.G.K and S.W.O. wrote the manuscript. All authors reviewed the manuscript.

Additional Information

The authors declare no competing financial interests.

Funding

This work was funded by National Research Foundation of Korea (NRF-2021R1A2C1007831).

References

1. Brant-Zawadzki, M., Gillan, G. D. & Nitz, W. R. MP RAGE: a three-dimensional, T1-weighted, gradient-echo sequence–initial experience in the brain. *Radiology* **182**, 769-775. https://doi.org/10.1148/radiology.182.3.1535892 (1992).
2. Hodel, J. *et al.* Imaging of the entire cerebrospinal fluid volume with a multistation 3D SPACE MR sequence: feasibility study in patients with hydrocephalus. *Eur Radiol* **23**, 1450-1458. https://doi.org/10.1007/s00330-012-2732-7 (2013).
3. Howell, B. R. *et al.* The UNC/UMN Baby Connectome Project (BCP): An overview of the study design and protocol development. *Neuroimage* **185**, 891-905. https://doi.org/10.1016/j.neuroimage.2018.03.049 (2019).

4. Chokshi, F. H., Sadigh, G., Carpenter, W. & Allen, J. W. Diagnostic Quality of 3D T2-SPACE Compared with T2-FSE in the Evaluation of Cervical Spine MRI Anatomy. *AJNR Am J Neuroradiol* **38**, 846-850. https://doi.org/10.3174/ajnr.A5080 (2017).
5. Jaspan, O. N., Fleysher, R. & Lipton, M. L. Compressed sensing MRI: a review of the clinical literature. *Br J Radiol* **88**, 20150487. https://doi.org/10.1259/bjr.20150487 (2015).
6. Lustig, M., Donoho, D. & Pauly, J. M. Sparse MRI: The application of compressed sensing for rapid MR imaging. *Magn Reson Med* **58**, 1182-1195. https://doi.org/10.1002/mrm.21391 (2007).
7. Glockner, J. F., Hu, H. H., Stanley, D. W., Angelos, L. & King, K. Parallel MR imaging: a user's guide. *Radiographics* **25**, 1279-1297. https://doi.org/10.1148/rg.255045202 (2005).
8. Benali, S. *et al.* Simultaneous multi-slice accelerated turbo spin echo of the knee in pediatric patients. *Skeletal Radiol* **47**, 821-831. https://doi.org/10.1007/s00256-017-2868-2 (2018).
9. Pipe, J. G. Motion correction with PROPELLER MRI: application to head motion and free-breathing cardiac imaging. *Magn Reson Med* **42**, 963-969. https://doi.org/10.1002/(sici)1522-2594(199911)42:5<963::aid-mrm17>3.0.co;2-l (1999).
10. Zhu, B., Liu, J. Z., Cauley, S. F., Rosen, B. R. & Rosen, M. S. Image reconstruction by domain-transform manifold learning. *Nature* **555**, 487-492. https://doi.org/10.1038/nature25988 (2018).
11. Lu, S. S. *et al.* Clinical Evaluation of Highly Accelerated Compressed Sensing Time-of-Flight MR Angiography for Intracranial Arterial Stenosis. *AJNR Am J Neuroradiol* **39**, 1833-1838. https://doi.org/10.3174/ajnr.A5786 (2018).
12. Toledano-Massiah, S. *et al.* Accuracy of the Compressed Sensing Accelerated 3D-FLAIR Sequence for the Detection of MS Plaques at 3T. *AJNR Am J Neuroradiol* **39**, 454-458. https://doi.org/10.3174/ajnr.A5517 (2018).
13. Suh, C. H., Jung, S. C., Lee, H. B. & Cho, S. J. High-Resolution Magnetic Resonance Imaging Using Compressed Sensing for Intracranial and Extracranial Arteries: Comparison with Conventional Parallel Imaging. *Korean J Radiol* **20**, 487-497. https://doi.org/10.3348/kjr.2018.0424 (2019).
14. Vranic, J. E. *et al.* Compressed Sensing-Sensitivity Encoding (CS-SENSE) Accelerated Brain Imaging: Reduced Scan Time without Reduced Image Quality. *AJNR Am J Neuroradiol* **40**, 92-98. https://doi.org/10.3174/ajnr.A5905 (2019).
15. Lee, S. M. *et al.* Image quality at synthetic brain magnetic resonance imaging in children. *Pediatr Radiol* **47**, 1638-1647. https://doi.org/10.1007/s00247-017-3913-y (2017).
16. He, L., Wang, J., Lu, Z. L., Kline-Fath, B. M. & Parikh, N. A. Optimization of magnetization-prepared rapid gradient echo (MP-RAGE) sequence for neonatal brain MRI. *Pediatr Radiol* **48**, 1139-1151. https://doi.org/10.1007/s00247-018-4140-x (2018).
17. Ahn, S. *et al.* Rapid MR imaging of the pediatric brain using the fast spin-echo technique. *American journal of neuroradiology* **13**, 1169-1177 (1992).
18. Lisanti, C., Carlin, C., Banks, K. P. & Wang, D. Normal MRI appearance and motion-related phenomena of CSF. *AJR Am J Roentgenol* **188**, 716-725. https://doi.org/10.2214/AJR.05.0003 (2007).
19. Kozak, B. M., Jaimes, C., Kirsch, J. & Gee, M. S. MRI Techniques to Decrease Imaging Times in Children. *Radiographics* **40**, 485-502. https://doi.org/10.1148/rg.2020190112 (2020).
20. Slovis, T. L. Sedation and anesthesia issues in pediatric imaging. *Pediatr Radiol* **41 Suppl 2**, 514-516. https://doi.org/10.1007/s00247-011-2115-2 (2011).

21. Ahmad, R., Hu, H. H., Krishnamurthy, R. & Krishnamurthy, R. Reducing sedation for pediatric body MRI using accelerated and abbreviated imaging protocols. *Pediatr Radiol* **48**, 37-49. https://doi.org/10.1007/s00247-017-3987-6 (2018).

22. Mönch, S. *et al.* Magnetic resonance imaging of the brain using compressed sensing–Quality assessment in daily clinical routine. *Clinical neuroradiology* **30**, 279-286. https://doi.org/10.1007/s00062-019-00789-x (2020).

23. Woodward, L. J., Anderson, P. J., Austin, N. C., Howard, K. & Inder, T. E. Neonatal MRI to predict neurodevelopmental outcomes in preterm infants. *N Engl J Med* **355**, 685-694. https://doi.org/10.1056/NEJMoa053792 (2006).

24. Moeskops, P. *et al.* Automatic segmentation of MR brain images of preterm infants using supervised classification. *Neuroimage* **118**, 628-641. https://doi.org/10.1016/j.neuroimage.2015.06.007 (2015).

25. Wang, S. *et al.* Quantitative assessment of myelination patterns in preterm neonates using T2-weighted MRI. *Sci Rep* **9**, 12938. https://doi.org/10.1038/s41598-019-49350-3 (2019).

26. Li, B., Li, H., Dong, L. & Huang, G. Fast carotid artery MR angiography with compressed sensing based three-dimensional time-of-flight sequence. *Magn Reson Imaging* **43**, 129-135. https://doi.org/10.1016/j.mri.2017.07.017 (2017).

27. Mönch, S. *et al.* Magnetic resonance imaging of the brain using compressed sensing–Quality assessment in daily clinical routine. *Clinical neuroradiology*, 1-8. https://doi.org/10.1007/s00062-019-00789-x (2019).

28. Lin, Z. *et al.* Clinical feasibility study of 3D intracranial magnetic resonance angiography using compressed sensing. *Journal of Magnetic Resonance Imaging* **50**, 1843-1851 (2019).

29. Iskandar, B. J. & Haughton, V. Age-related variations in peak cerebrospinal fluid velocities in the foramen magnum. *J Neurosurg* **103**, 508-511. https://doi.org/10.3171/ped.2005.103.6.0508 (2005).

30. Sartoretti, T. *et al.* Common artefacts encountered on images acquired with combined compressed sensing and SENSE. *Insights Imaging* **9**, 1107-1115. https://doi.org/10.1007/s13244-018-0668-4 (2018).

Figures

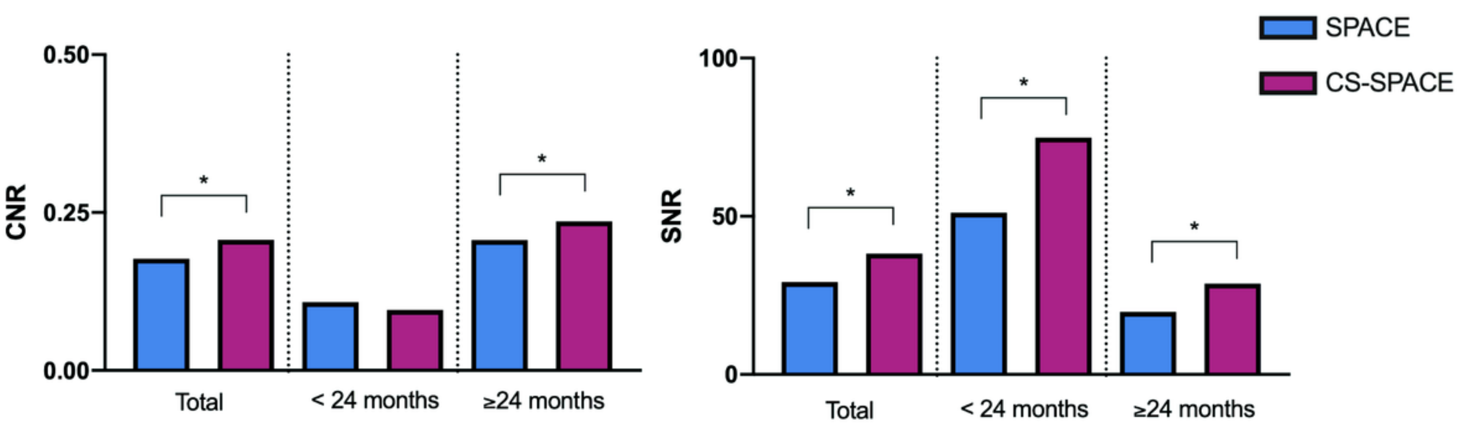

Figure 1

Boxplots showing the quantitative image quality comparison between SPACE and CS-SPACE. The asterisks indicate P value < .05. CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio.

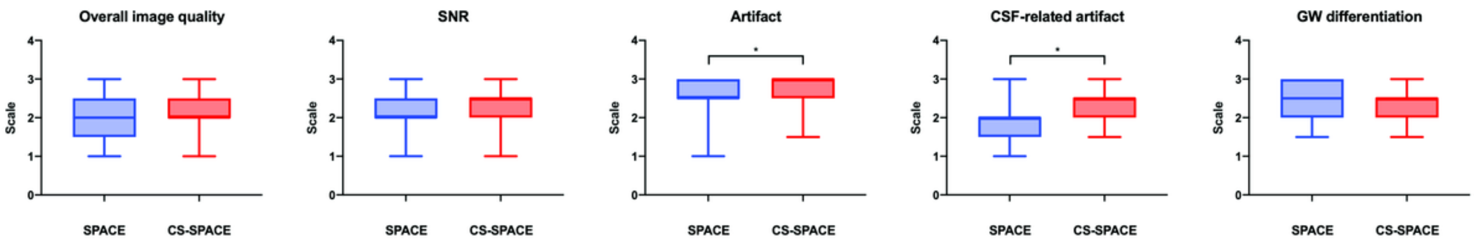

Figure 2

Bar charts showing the qualitative image quality comparison between SPACE and CS-SPACE. The asterisks indicate P value < .05. SNR, signal-to-noise ratio; CSF, cerebrospinal fluid; GW, grey-white matter.

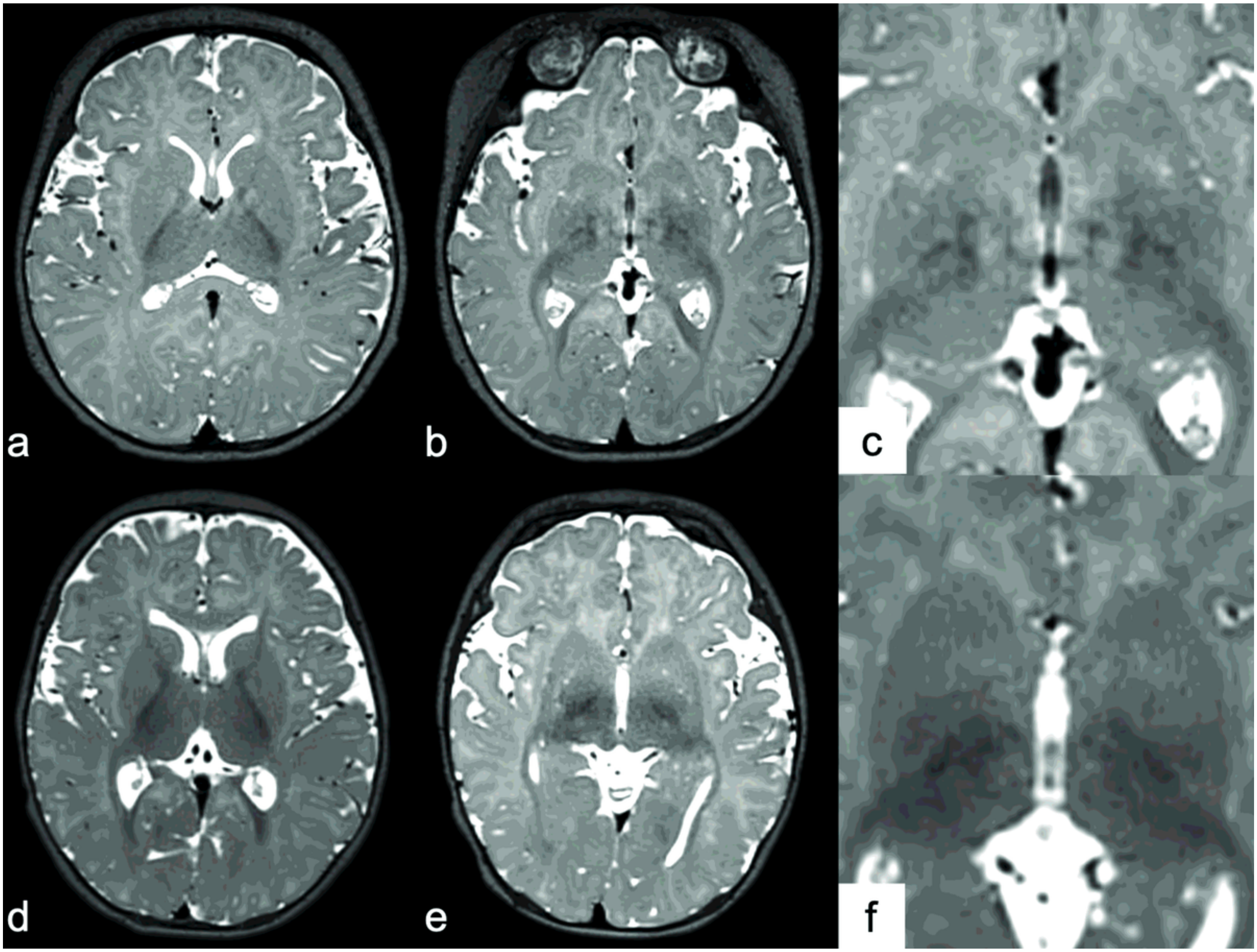

Figure 3

SPACE (a, b, c) and CS-SPACE (d, e, f) images from two 5-month-old females. CNR and SNR were higher with CS-SPACE compared to SPACE (CNR, 0.084 vs. 0.074; SNR, 42.5 vs. 20.2). CSF-related artifacts inside and around the third ventricle are shown in c and f. CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio; CSF, cerebrospinal fluid.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplemental0727.docx