Accelerated 3D T2-weighted images using compressed sensing for pediatric brain imaging

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Abstract
Purpose The purpose of this study was to compare the image quality of the 3D T2-weighted images accelerated using conventional method (CAI-SPACE) with the images accelerated using compressed sensing (CS-SPACE) in pediatric brain imaging.

Methods A total of 116 brain MRI (53 with CAI-SPACE and 63 with CS-SPACE) were obtained from children 16 years old or younger. Quantitative image quality was evaluated using the apparent signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). The sequences were qualitatively evaluated for overall image quality, general artifact, cerebrospinal fluid (CSF)-related artifact, and grey-white matter differentiation. The two sequences were compared for the total and two age groups (<24 months vs. ≥24 months).

Results Compressed sensing application in 3D T2-weighted imaging resulted in 8.5% reduction in scanning time. Quantitative image quality analysis showed higher apparent SNR (median [Interquartile range]; 29 [25] vs. 23 [14], P = 0.005) and CNR (0.231 [0.121] vs. 0.165 [0.120], P = 0.027) with CS-SPACE compared to CAI-SPACE. Qualitative image quality analysis showed better image quality with CS-SPACE for general (P = 0.024) and CSF-related artifact (P < 0.001). CSF-related artifacts reduction was prominent in the older age group (≥24 months). Overall image quality (P = 0.162) and grey-white matter differentiation (P = 0.397) were comparable between CAI-SPACE and CS-SPACE.

Conclusion Compressed sensing application in 3D T2-weighted images modestly reduced acquisition time and lowered CSF-related artifact compared to conventional images of the pediatric brain.

Keywords Magnetic resonance imaging · Children · Image enhancement · Neuroimaging · Acceleration

Introduction
High-resolution three-dimensional (3D) imaging is now feasible in pediatric 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 pediatric neuroimaging is the magnetization-prepared rapid gradient echo (MPRAGE) sequence, which generates T1-weighted images (T1WI) [1]. Compared to 3D T1WI, 3D T2-weighted 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 pediatric 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 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 nonlinear iterative reconstruction of undersampled k-space data [6, 15, 16]. 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. Neuroimaging applications are different for children than adults, since children show different conditions during scanning as well as different brain tissue contrasts that are 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 MRI of children (16 years or under) obtained from May 2019 to February 2020 using a 3 T scanner (Vida; Siemens, Erlangen, German). We included brain MRI obtained between May 2019 and October 2019 using the conventional 3D T2-weighted turbo-spin-echo sequence with high sampling efficiency accelerated using the Controlled Aliasing in Parallel Imaging Results in Higher Acceleration (CAIPIRINHA) method (CAI-SPACE) and brain MRI obtained between November 2019 and February 2020 using accelerated SPACE with compressed sensing (CS-SPACE). We included patients who underwent both CAI-SPACE and CS-SPACE between August 2019 and October 2019. Demographic information was collected through a review of medical records. Patients were grouped according to sequence (CAI-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 3 T MRI with a 64-channel head coil. The spatial resolution of CAI-SPACE and CS-SPACE were the same (matrix, 320×320×208; FOV, 256×256×166.4 mm³; voxel size, 0.4×0.4×0.8 mm³). The repetition time (TR) was longer (5000 ms vs. 3500 ms) and the turbo factor was smaller (230 vs. 290) for CS-SPACE compared to CAI-SPACE. This difference occurred because we needed to maintain image quality as much as possible with CS-SPACE being obtained for actual clinical purposes, and because we were not sure how much CS application would degrade image quality. We first applied a higher acceleration factor of 7 to reduce scanning time, then selected a longer TR and smaller turbo factor to compensate for the potential degrade of the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) based on our clinical experience. 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 3 min and 13 s and for CAI-SPACE was 3 min and 31 s, resulting in an 8.5% reduction in scanning time when CS was applied. An incoherent undersampling pattern using a Poisson-disc variable density pattern with elliptical scanning was applied to acquire CS-SPACE k-space data. For the reconstruction, L1 regularization with the redundant Haar wavelet transform was applied. The denoising mode (regularization value) was set to run automatically [15]. Restore pulses were used for both sequences.

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,

| Table 1 Parameters of CAI-SPACE and CS-SPACE |
|---------------------------------------------|-----------------|-----------------|
| Echo time (ms)                              | 502             | 450             |
| Repetition time (ms)                        | 3500            | 5000            |
| Flip angle                                  | Variable        | Variable        |
| Matrix                                      | 320×320×208     | 320×320×208     |
| Field of view (mm³)                         | 256×256×166.4   | 256×256×166.4   |
| Voxel size (mm³)                            | 0.8×0.8×0.8     | 0.8×0.8×0.8     |
| Acceleration factor                         | 4               | 7               |
| Turbo factor                                | 290             | 230             |
| Echo spacing (ms)                           | 3.72            | 3.72            |
| Echo train duration (ms)                    | 1045            | 859             |
| Scan time                                   | 3 min 31 s      | 3 min 13 s      |
intravenous midazolam (0.025–0.05 mg/kg) was used. Since the number of sedated patients could affect the nature of the artifacts observed, we compared the number of patients who were sedated in the CS-SPACE and CAI-SPACE groups.

**Image quality evaluation**

A flow chart of the image quality evaluation process is presented in Fig. 1. 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. The 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 [17]. The SNR was estimated as white matter intensities divided by the standard deviation of white matter [18]. The denoising effect of CS impacts SNR and the resulting value should be termed apparent SNR instead of SNR when CS is used [6]. For interobserver agreement evaluation, two radiologists (with 10 years of experience in pediatric neuroradiology and with 13 years of experience in neuroradiology) drew ROIs. For intraobserver agreement evaluation, one radiologist drew the second ROIs after two weeks. Representative images for the ROIs are shown in Supplementary Fig. 1.

For qualitative analysis, the two radiologists (one with 10 years of experience in pediatric neuroradiology [radiologist 1] and one with 13 years of experience in neuroradiology [radiologist 2]) performed visual assessments. MR images were analyzed blindly and independently in random order. The sequences were qualitatively evaluated with 3-point scales for overall image quality, general artifacts, cerebrospinal fluid (CSF)-related artifacts, and grey-white matter differentiation. The grades for image quality and grey-white matter differentiation were defined as follows: 1 = poor, 2 = adequate, 3 = good. In terms of grey-white matter differentiation, both contrast and sharpness between deep grey matter and surrounding white matter were assessed. The grades for general and CSF-related artifacts were defined as follows: 1 = severe artifact, 2 = moderate artifact, 3 = mild or no artifact. For overall image quality, images were defined as being of poor (grade 1) quality when they were of non-diagnostic quality or insufficient quality for diagnostic purposes, adequate (grade 2) when sufficient for diagnostic purposes, but with perceptible image degradations, and good (grade 3) when only minor image degradations or no image degradations were observed. For general artifacts, the degree of motion or truncation artifacts were evaluated [19]. For CSF-related artifacts, signal change and distortion inside and around the third ventricle were evaluated [20]. Representative images of the image quality scales are presented in Supplementary Fig. 2.

Image quality was compared for the total study population and 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 apparent SNR) were compared between CAI-SPACE and CS-SPACE using the Mann–Whitney test. Gender, use of sedation, and qualitative image analysis variables were compared between CAI-SPACE and CS-SPACE using either the Chi-square or Fisher’s exact test. To evaluate inter- and intraobserver agreement for the measurements from the ROIs, the intraclass correlation coefficient (ICC) was obtained. Level of agreements were defined as poor (0.00–0.20), slight (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), substantial (0.61–0.80),...
and almost perfect (0.81–1.00). The mean values of the two radiologists’ qualitative scales were compared between CAI-SPACE and CS-SPACE using the Mann–Whitney test. To compare image quality in patients who underwent both CAI-SPACE and CS-SPACE sequences, the Wilcoxon Signed-Rank test was used. SPSS (version 27.0, IBM, Armonk, New York, USA) were used for analysis and graphs were prepared using Graphpad prism software (version 8.4.2, San Diego, USA). P values < 0.05 were considered statistically significant.

Results

Patients

A total of 116 brain MRI scans were performed with either CAI-SPACE or CS-SPACE. Children underwent brain MRI for various indications, with prematurity, headaches, seizure, and trauma being the most common. There were 53 brain MRI scans obtained with the CAI-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 = 0.305). Sixty-two subjects underwent MR with sedation. For total patients, the use of sedation did not differ between CAI-SPACE and CS-SPACE (CAI-SPACE, 53% vs. CS-SPACE, 49%, P > 0.999). However, when the two age groups were compared, younger patients were more frequently sedated in the CS-SPACE group than the CAI-SPACE group (CAI-SPACE, 50% vs. CS-SPACE, 92%, P = 0.020). In older patients, the use of sedation did not differ between the two sequences (CAI-SPACE, 54% vs. CS-SPACE, 44%, P = 0.391).

Table 2 Demographic characteristics

|                | CAI-SPACE (n = 53) | CS-SPACE (n = 63) | P Value |
|----------------|-------------------|------------------|---------|
| Age (month)    | 76±67             | 89±65            | 0.305   |
| Age group      |                   |                  |         |
| < 24 months    | 16 (30%)          | 13 (21%)         | 0.333   |
| ≥ 24 months    | 37 (70%)          | 50 (79%)         |         |
| Gender         |                   |                  | > 0.999 |
| Male           | 27 (51%)          | 31 (49%)         |         |
| Female         | 26 (49%)          | 32 (51%)         |         |
| Sedated subjects |                |                  |         |
| Total          | 28 (53%)          | 34 (49%)         | > 0.999 |
| < 24 months    | 8 (50%)           | 12 (92%)         | 0.020   |
| ≥ 24 months    | 20 (54%)          | 22 (44%)         | 0.391   |

Data – number (percentage)

Quantitative image quality

Quantitative image quality of CAI-SPACE and CS-SPACE are summarized in Tables 3 and 4 and Fig. 2. Regarding total subjects, both CNR (median [interquartile range]; 0.231 [0.121] vs. 0.165 [0.120], P = 0.027) and apparent SNR (29 [25] vs. 23 [14], P = 0.005) were significantly higher with CS-SPACE than CAI-SPACE (Table 3 and Fig. 2). When quantitative image quality was compared in patients under 24 months and patients 24 months or older, a different trend was seen for CNR according to age but not for apparent SNR. In patients under 24 months, apparent SNR tended to be higher with CS-SPACE than CAI-SPACE (64 [49] vs. 36 [33], P = 0.050), but CNR showed no significant difference between the two sequences (0.088 [0.067] vs. 0.111 [0.097], P = 0.630) (Table 4). In patients 24 months and older, both CNR (0.242 [0.064] vs. 0.208 [0.115], P = 0.048) and apparent SNR (27 [16] vs. 19 [8], P < 0.001) were significantly higher with CS-SPACE compared to CAI-SPACE.

Substantial to almost perfect inter- and intra-observer agreements were achieved for CNR and apparent SNR. ICC values for interobserver agreement were 0.854 (P < 0.001) for CNR and 0.637 (P < 0.001) for apparent SNR. ICC values for intraobserver agreement were 0.961 (P < 0.001) for CNR and 0.608 (P < 0.001) for apparent SNR.

Table 3 Image quality comparison between CAI-SPACE and CS-SPACE in total subjects

|                | CAI-SPACE (n = 53) | CS-SPACE (n = 63) | P Value |
|----------------|-------------------|------------------|---------|
| Quantitative parameters |                   |                  |         |
| CNR            | 0.165 (0.120)     | 0.231 (0.121)    | 0.027   |
| Apparent SNR   | 23 (14)           | 29 (25)          | 0.005   |
| Qualitative parameters |               |                  |         |
| Overall image quality |                   |                  |         |
| Radiologist 1  | 20/21/12          | 8/39/16          | 0.006   |
| Radiologist 2  | 12/20/21          | 9/28/26          | 0.486   |
| Artifact       |                   |                  |         |
| Radiologist 1  | 8/14/31           | 2/16/45          | 0.064   |
| Radiologist 2  | 4/13/36           | 2/8/53           | 0.118   |
| CSF-related artifact |             |                  |         |
| Radiologist 1  | 21/23/9           | 3/37/23          | < 0.001 |
| Radiologist 2  | 9/29/15           | 0/25/38          | < 0.001 |
| GW differentiation |                |                  |         |
| Radiologist 1  | 3/33/17           | 2/40/21          | 0.805   |
| Radiologist 2  | 0/19/34           | 0/33/30          | 0.110   |

Values are in median (interquartile range) or number of images assigned in 3-point scales (scale 1/2/3); CNR contrast-to-noise ratio, SNR signal-to-noise ratio, CSF cerebrospinal fluid, GW grey-white matter
Qualitative image quality

The qualitative image qualities of CAI-SPACE and CS-SPACE in total subjects are summarized in Table 3. CSF-related artifacts between CS-SPACE and CAI-SPACE images were rated differently by both radiologists \((P < 0.001)\). When mean scale values by the radiologists were compared (Fig. 3), general artifacts \((3.0 [0.5] \text{ vs. } 2.5 [0.5], P = 0.024)\) and CSF-related artifacts \((2.5 [0.5] \text{ vs. } 2.0 [0.5], P < 0.001)\) showed higher values with CS-SPACE compared to CAI-SPACE. Overall image quality (CAI-SPACE vs. CS-SPACE; \(2.0 [1.0] \text{ vs. } 2.0 [0.5], P = 0.162\)) and grey-white matter differentiation \((2.5 [1.0] \text{ vs. } 2.5 [0.5], P = 0.397)\) did not show significant differences.

The comparison of qualitative image quality according to age groups is summarized in Table 4. In patients under 24 months, general artifacts were rated higher (radiologist 1, \(P = 0.047\)) or comparable (radiologist 2, \(P = 0.426\)) with CS-SPACE than CAI-SPACE. In patients 24 months or older, CSF-related artifacts were rated with higher scores with CS-SPACE than CAI-SPACE (both radiologists, \(P < 0.001\)). 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 CAI-SPACE and

### Table 4 Image quality comparison between CAI-SPACE and CS-SPACE in age groups

|                      | Age < 24 months |                   | Age ≥ 24 months |                   |
|----------------------|-----------------|------------------|-----------------|------------------|
|                      | CAI-SPACE \((n = 16)\) | CS-SPACE \((n = 13)\) | \(P \text{ Value}\) | CAI-SPACE \((n = 37)\) | CS-SPACE \((n = 50)\) | \(P \text{ Value}\) |
| **Quantitative parameters** |                 |                   |                 |                 |
| CNR                  | \(0.111 (0.097)\) | \(0.088 (0.067)\) | 0.630           | \(0.208 (0.115)\) | \(0.242 (0.064)\) | 0.048          |
| Apparent SNR         | 36 (33)         | 64 (49)          | 0.050           | 19 (8)          | 27 (16)          | <0.001         |
| **Qualitative parameters** |                 |                   |                 |                 |
| Overall image quality |                 |                   |                 |                 |
| Radiologist 1        | 7/6/3           | 1/9/3            | 0.089           | 13/15/9         | 7/30/13          | 0.057          |
| Radiologist 2        | 3/4/9           | 1/7/5            | 0.262           | 9/16/12         | 8/21/21          | 0.529          |
| Artifact             |                 |                   |                 |                 |
| Radiologist 1        | 2/6/8           | 0/1/12           | 0.047           | 6/8/23          | 2/15/33          | 0.131          |
| Radiologist 2        | 1/3/12          | 0/1/12           | 0.426           | 3/10/24         | 2/7/41           | 0.191          |
| CSF-related artifact |                 |                   |                 |                 |
| Radiologist 1        | 3/6/7           | 0/8/5            | 0.188           | 18/17/2         | 3/29/18          | <0.001         |
| Radiologist 2        | 0/4/12          | 0/4/9            | 0.811           | 9/25/3          | 0/21/29          | <0.001         |
| GW differentiation    |                 |                   |                 |                 |
| Radiologist 1        | 3/9/4           | 2/10/1           | 0.415           | 0/24/13         | 0/30/20          | 0.811          |
| Radiologist 2        | 0/6/10          | 0/8/5            | 0.360           | 0/13/24         | 0/25/25          | 0.245          |

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

![Fig. 2 Boxplots showing the quantitative image quality comparison between CAI-SPACE and CS-SPACE. The asterisks indicate \(P \text{ value} < 0.05\). CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio](image-url)
CS-SPACE in both age groups. Representative images of CAI-SPACE and CS-SPACE are shown in Supplementary Fig. 3.

**Image quality comparison in patients who underwent both CAI-SPACE and CS-SPACE**

There were 13 patients who underwent both CAI-SPACE and CS-SPACE. Demographics and image quality are compared between the two sequences in Table 5. The median (interquartile range) age was 155 months and there were 8 males. When quantitative image quality was compared, apparent SNR was significant higher with CS-SPACE compared to CAI-SPACE (CNR, 0.138 vs. 0.247; apparent SNR, 62 vs. 141). The artifacts inside and around the ventricle are shown in CAI-SPACE (A, arrows; CSF-related artifact grade 2) but to a lesser degree in CS-SPACE (B; CSF-related artifact grade 3). CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio; CSF, cerebrospinal fluid.

**Fig. 3** Bar charts showing the qualitative image quality comparison between CAI-SPACE and CS-SPACE. The asterisks indicate $P$ value < 0.05. CSF, cerebrospinal fluid; GW, grey-white matter

**Fig. 4** CAI-SPACE (A) and CS-SPACE (B) images of a 9-year-old male. CNR and apparent SNR were higher with CS-SPACE compared to CAI-SPACE (CNR, 0.138 vs. 0.247; apparent SNR, 62 vs. 141). The artifacts inside and around the ventricle are shown in CAI-SPACE (A, arrows; CSF-related artifact grade 2) but to a lesser degree in CS-SPACE (B; CSF-related artifact grade 3). CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio; CSF, cerebrospinal fluid

**Table 5** Demographic data and image quality comparison between CAI-SPACE and CS-SPACE in patients who underwent both sequences

| Demographics | CAI-SPACE | CS-SPACE | $P$ Value |
|--------------|-----------|----------|-----------|
| Age (month)  | 155 (81)  | 155 (81) | 0.861     |
| Gender (male:female) | 8:5       | 8:5      | 0.317     |

| Image quality evaluation | CAI-SPACE | CS-SPACE | $P$ Value |
|--------------------------|-----------|----------|-----------|
| Quantitative parameters  |           |          |           |
| CNR                      | 0.222 (0.067) | 0.230 (0.050) | 0.861     |
| Apparent SNR             | 68 (41)   | 100 (47) | 0.006     |
| Qualitative parameters   |           |          |           |
| Overall image quality    | 3 (0)     | 3 (0)    | 0.317     |
| Artifact                 | 3 (1)     | 3 (1)    | >0.999    |
| CSF-related artifact     | 2 (1)     | 3 (0)    | 0.007     |
| GW differentiation       | 3 (1)     | 3 (1)    | >0.999    |

Values are in median (interquartile range); CNR contrast-to-noise ratio, SNR signal-to-noise ratio, CSF cerebrospinal fluid, GW grey-white matter
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 pediatric brain imaging. With CS, scanning times were reduced by approximately 9% which resulted in higher or comparable image quality. When image quality was compared in the large number of patients who underwent either CAI-SPACE or CS-SPACE, apparent SNR was higher with CS-SPACE compared to CAI-SPACE. This difference 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. This trend of higher apparent SNR and reduced CSF artifacts was consistent when the two sequences were compared in patients who underwent both. The major findings of our study are that using CS in 3D T2-weighted imaging resulted in reduced scanning times and improved CSF-related artifacts.

We found significant reduction of CSF-related artifacts after using CS. T2WI is subject to flow and motion artifacts [21]. A similar effect of reduced ghost artifacts was observed in a prior study that applied CS to sensitivity encoding (SENSE) for patients with suspected neurovascular compression syndrome [22]. CSF pulsation is a periodic motion that can lead to ghosting artifacts due to the turbulent flow effect [20]. Ghost artifacts occur along the phase-encoding direction because phase information is acquired over an entire scan [20]. With periodic motion, coherent k-space undersampling acquisition such as CAIPIRINA may lead to discrete ghost artifacts on images. In comparison, CS uses the pseudo-random sampling in k-space so artifacts are distributed as diffuse noise across the entire image. With CS, this diffuse noise can be removed or reduced by wavelet transform and iterative reconstruction.

On the other hand, CS did 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 [23]. 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 studies on this topic are necessary with a larger number of patients who are both sedated and not sedated.

Reducing scanning time is particularly important in pediatric MRI studies [24]. Various acceleration techniques have been developed for faster MR studies such as parallel imaging, radial sampling, spiral sampling, and recently, CS [25]. CAIPIRINA, the acceleration method we used for CAI-SPACE, is a parallel imaging technique. Acquired points in k-space are shifted from one to another in CAIPIRINA [26]. On the other hand, CS generates images from random or pseudo-random undersampled k-space data using an iterative nonlinear method [15, 16, 21]. As this allows high temporal resolution, CS has been applied to cardiovascular and abdominal imaging in pediatric patients [25].

In this study, 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 [27]. 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 pediatric and adult populations include 3D images rather than 2D images. In terms of T1WI, 3D imaging is considered the standard protocol for neonates, because it can identify more white matter punctate lesions that are frequently involved in neonates with ischemic insult [28]. 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 [29] or for assessing myelination degree in young populations that have not reached full myelination [30]. 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 to 70% using CS [12, 27, 31], our protocol resulted in approximately 9% reduction. This is mainly due to the longer TR set for CS-SPACE than CAI-SPACE (5000 ms vs. 3500 ms). The longer TR and shorter turbo-factor of CS-SPACE compared to CAI-SPACE could result in further reductions of the specific absorption rate (SAR) which would be especially beneficial for pediatric scans. However, further scan time reduction and overall improved scan efficiency without degradations in image quality could be achieved with a shorter TR. This is supported by the significantly higher apparent SNR in subjects less than 24 months of age. In this study, 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 pediatric brain MRI is approximately 2 min and 30 s to 3 min and 35 s and our scanning time was 3 min 13 s [17]. However, the selection of a longer TR and shorter turbo factor was based on our clinical experience, and we did not remove a restore pulse for longer TR. Increasing the number of averages, not TR, could be another option to preserve image quality when applying CS. Further studies that discover ways to
achieve additional time reduction are needed with other parameters being varied in experiments on the optimal TR and turbo-factor selection for CS.

Although the CNR values in the total and older age group were higher in CS-SPACE compared to CAI-SPACE, the younger age group showed opposite result without statistical significance. Brain tissue in infants (i.e., age < 24 months) has high water content and T2WI contrast differ between infants and older children [32]. Accordingly, shorter TR are used for T2WI of younger children [17]. Therefore, a longer TR may have affected the CNRs of the two age groups. As discussed earlier, further studies have to be performed to find distinct and optimal parameters for younger children with higher water content.

There are several limitations to our study. Firstly, we compared the sequences in two different cohorts for two different study periods. Several other studies for pediatric image quality comparison have been performed as such to avoid lengthening the scanning time for one subject. Although we included some subjects who underwent both sequences, a prospective study that applies the two sequences in a larger identical cohort is needed to prove the improved efficacy and image quality of CS. Secondly, there was large variation in age as we included patients with various degrees of brain maturation and scanning status. As different results were found for each age group, large-scale studies that classify patients into more narrow age ranges could be needed. For example, sedation status can improve image quality by reducing motion during scanning and shorter scanning times can also result in fewer motion artifacts. As shown in our results, the CS-SPACE group of patients younger than 24 months of age included a greater number of sedated subjects, and this could have resulted in lower artifacts. Thirdly, we did not evaluate sharpness independently or specific artifacts that would be subject to the two sequences. A previous study on time-of-flight MR angiography showed that edge sharpness was better with CS than conventional MR angiography. However, the study used higher reconstruction spatial resolution with CS. Regarding artifacts, 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 center of the transverse reconstructed images, respectively [33]. Further studies that compare sharpness and artifacts qualitatively in 3D T2-weighted images for brain imaging will be needed. Lastly, acquiring SNR in CS-applied sequences is a potential limitation. This is because CS generates images by an iterative nonlinear method. Although we introduced the term ‘apparent SNR’ instead of SNR for quantitative image quality comparison, the nonlinear reconstruction method process by CS makes quantitative SNR measurement less reliable.

In conclusion, the application of CS to high-resolution 3D T2-weighted imaging with a longer TR and smaller turbo factor did not degrade image quality in children and resulted in modest reductions in scanning time. In addition, CSF-related artifacts were improved when CS was applied to 3D T2-weighted imaging. CS technique has the potential to increase the routine use of high-resolution 3D T2-weighted imaging in pediatric brain MRI.

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Declarations

Conflict of interest The authors declare no competing interests.

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