Quiet Diffusion-weighted MR Imaging of the Brain for Pediatric Patients with Moyamoya Disease

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Purpose: Diffusion-weighted MRI (DWI) is an essential sequence for evaluating pediatric patients with moyamoya disease (MMD); however, acoustic noise associated with DWI may lead to motion artifact. Compared with conventional DWI (cDWI), quiet DWI (qDWI) is considered less noisy and able to keep children more relaxed and stable. This study aimed to evaluate the suitability of qDWI compared with cDWI for pediatric patients with MMD.

Methods: In this observational study, MR examinations of the brain were performed either with or without sedation in pediatric patients with MMD between September 2017 and August 2018. Three neuroradiologists independently evaluated the images for artifacts and restricted diffusion in the brain. The differences between qDWI and cDWI were compared statistically using a chi-square test.

Results: One-hundred and six MR scans of 56 patients with MMD (38 scans of 15 sedated patients: 6 boys and 9 girls; mean age, 5.2 years; range, 1–9 years; and 68 scans of 42 unsedated patients: 19 boys and 23 girls; mean age, 10.7 years; range, 7–16 years) were evaluated. MR examinations were performed either with or without sedation (except in one patient). In sedated patients, no artifact other than susceptibility was observed on qDWI, whereas four artifacts were observed on cDWI ($P$ = .04). One patient awoke from sedation during cDWI scanning, while no patient awoke from sedation during qDWI acquisition. For unsedated patients, three scans showed artifacts on qDWI, whereas two scans showed artifacts on cDWI ($P$ = .65). Regarding restricted diffusion, qDWI revealed three cases, while two cases were found on cDWI ($P$ = .66).

Conclusion: qDWI induced fewer artifacts compared with cDWI in sedated patients, and similar frequencies of artifacts were induced by qDWI and by cDWI in unsedated patients. qDWI showed restricted diffusion comparable to cDWI.

Keywords: acoustic noise reduction, diffusion-weighted magnetic resonance imaging, pediatric patient, moyamoya disease, sedation

Introduction

Moyamoya disease (MMD) is characterized by progressive steno-occlusion of the intracranial internal carotid arteries and their proximal branches with prominent collateral artery formation.1 MMD affects children, as well as adults, and shows different clinical manifestations depending on the population: ischemic symptoms predominate in children, and intracranial hemorrhage is more frequent in adults than in children.2–8 Most commonly affected areas are the frontal and parietal lobes, where the cerebral ischemia causes symptoms, such as hemiparesis and cognitive impairment.9–13 For pediatric patients with MMD, comprehensive evaluation including brain MR is necessary to make the diagnosis and formulate the most appropriate treatment strategy.12
Diffusion-weighted MRI (DWI) is an essential sequence performed in the pre- and post-operative management of ischemic stroke patients who undergo bypass surgery.\textsuperscript{14} DWI is usually acquired with single-shot echo-planar imaging.\textsuperscript{15–17} The echo-planar imaging sequence relies on fast switching of gradient amplitudes, generating a level of acoustic noise that is the highest among the routine brain MRI sequences.\textsuperscript{18–21} Since the noise is uncomfortable, children find it difficult to remain still during image acquisition, and young children, in particular, need sedation to eliminate motion artifact in the images.\textsuperscript{22,23} However, large noise created by conventional DWI (cDWI) can interfere with stable sedation.

Quiet DWI (qDWI) with acoustic noise reduction has recently been introduced to clinical practice and is achievable using readout-segmented echo-planar imaging scanning in combination with partial-Fourier acquisition in the phase-encoding direction.\textsuperscript{24,25} The acoustic noise is lessened by reducing the forces generated in the gradient coils.\textsuperscript{21,26} Compared with cDWI, qDWI is considered a gentler sequence for pediatric patients, with less risk of sedated patients waking during the acquisition. However, to our knowledge, few reports have assessed the advantages of qDWI at 3T.

Therefore, the purpose of this study was to evaluate the suitability of qDWI compared with cDWI at 3T for pediatric patients with MMD, specifically in terms of artifacts and detection of lesions that have restricted diffusion.

Materials and Methods

This observational study was approved by our Institutional Review Board, and the need to obtain written informed consent was waived. The opportunity to opt out was available to patients via the website.

Patients

We evaluated consecutive brain MR examinations of pediatric patients with MMD between August 2017 and August 2018. We included all patients who had brain MR examinations during this period and did not exclude any patients. Patients below 7 years of age were sedated during scanning, and those above 7 years old who could not keep still were also sedated. A diagnosis of MMD was determined on the basis of previously published criteria.\textsuperscript{27}

Image acquisition

MRI was obtained using 3T units (MAGNETOM Prisma and MAGNETOM Skyra; Siemens Healthineers, Erlangen, Germany) and the following sequences were performed: time-of-flight MR angiography (TOF-MRA), axial susceptibility-weighted imaging (SWI), axial T2-weighted imaging (T2WI), axial fluid-attenuated inversion recovery (FLAIR), 3D T1-weighted imaging (T1WI), axial qDWI, and axial cDWI. The protocol for pediatric patients with MMD used quiet methods for all imaging sequences, except TOF-MRA and cDWI.\textsuperscript{25} The acquisition parameters for the qDWI sequence were as follows: TR, 5440 msec for MAGNETOM Prisma and 7370 msec for MAGNETOM Skyra; TE, 61 msec for MAGNETOM Prisma and 67 msec for MAGNETOM Skyra; slice thickness, 3 mm; slice gap, 1mm; acquisition matrix, 160 × 160; FOV, 220 × 220 mm; phase partial Fourier, 7/8; number of slices, 35; bandwidth 780 Hz/pixel; averages, 1; scan time, 1:56 (2:36) sec; parallel acquisition technique, 2; readout segments, 3; reference lines, 53; motion probing gradients, orthogonal; scan time, 1:56 (2:36) sec; phase-encoding direction, anterior-posterior.

The numbers in parentheses represent the imaging parameters on Magnetom Skyra. cDWI, conventional diffusion-weighted MRI; qDWI, quiet diffusion-weighted MRI.

Table 1 Parameters in qDWI and cDWI sequences

| Parameter                  | qDWI          | cDWI          |
|----------------------------|---------------|---------------|
| TR (msec)                  | 5440 (7370)   | 4900          |
| TE (msec)                  | 61 (67)       | 75            |
| Slice thickness (mm)       | 3             | 3             |
| Slice gap (mm)             | 1             | 1             |
| Acquisition matrix         | 160 × 160     | 160 × 160     |
| FOV (mm)                   | 220 × 220     | 220 × 220     |
| Phase partial Fourier      | 7/8           | 7/8           |
| Number of slices           | 35            | 35            |
| Bandwidth (Hz/Px)          | 780           | 1360          |
| Averages                   | 1             | 5             |
| Scan time                  | 1:56 (2:36)   | 2:04          |
| Parallel acquisition       | 2             | 3             |
| technique                 |               |               |
| Readout segments           | 3             | 1             |
| Reference lines            | 53            | 39            |
| Motion probing gradients   | Orthogonal    | Orthogonal    |
| phase-encoding direction   | Anterior-posterior | Anterior-posterior |

The acquisition parameters for the cDWI sequence were as follows: TR, 4900 msec; echo time, 75 msec; slice thickness, 3 mm; slice gap, 1mm; acquisition matrix, 160 × 160; FOV, 220 × 220 mm; parallel acquisition technique, 2; readout segments, 3; reference lines, 53; motion probing gradients, orthogonal. Phase-encoding direction, anterior-posterior.
**Image analysis**

Three radiologists (S.N., G.O., and S.O., with 13, 10, and 8 years of experience in neuroradiology, respectively), who were blinded to the sequence type, reviewed the images independently. qDWI and cDWI were evaluated independently with an interval period of longer than four weeks because serial evaluation of these images in the same patient might be remembered and cause bias. Artifacts were defined as abnormal image findings that displayed blurring and ghosting, and image distortion induced by susceptibility associated with metal or air-containing paranasal sinuses was not considered in the evaluation. Artifacts were evaluated separately in the sedated and unsedated patients. Restricted diffusion in the brain was also evaluated by viewing apparent diffusion coefficient maps, as well as DWI. We focused on distinct artifacts and lesions with restricted diffusion. Indistinct artifacts were regarded as absent because they were not considered to affect radiologic interpretations.

**Quantitative evaluation of acoustic noise and SNR**

Acoustic noise of qDWI and cDWI was measured on the MRI table at a distance of 2 meters from the isocenter of the magnet, while a copper sulfate phantom was scanned. A sound level meter of NL-32 (Rion, Tokyo, Japan) was used. SNR maps of qDWI and cDWI were obtained from 10 consecutive measurements by the temporal SNR method. On every SNR map, the single slice in the middle was used for the ROI analysis. As shown in Supplementary Fig. 1, eight circular ROIs of the same size were placed using ImageJ (ver. 1.52a; [https://imagej.nih.gov/ij/](https://imagej.nih.gov/ij/)). Four ROIs were placed in the center, which yielded the central ROI. The other ROIs were placed on the four edges of the top, bottom, left, and right sides, which yielded the peripheral ROI. The ROI values (mean ± standard deviation) were obtained.

**Results**

**Patient demographics**

We evaluated 106 MR scans of 56 patients with MMD (Fig. 1 and Table 2): 38 scans of 15 sedated patients (6 boys and 9 girls; mean age, 5.2 years; range, 1–9 years) and 68 scans of 42 unsedated patients (19 boys and 23 girls; mean age, 10.7 years; range, 7–16 years). Thiopental sodium was mainly used for sedation, and dexmedetomidine hydrochloride was used in combination with thiopental sodium if necessary. Midazolam was used in one patient with bronchial asthma. The minimum dosage of sedative was necessary. In all patients (except one girl), the MR examination was performed either with or
Table 2 Patient demographics

| Variable               | Sedated | Unsedated | Overall |
|------------------------|---------|-----------|---------|
| No. of patients with MMD | 15      | 42        | 56*     |
| Boy                    | 6       | 19        | 25      |
| Girl                   | 9       | 23        | 32      |
| Age (years)            | 5.2 (1–9) | 10.7 (7–16) | 9.2 (1–16) |
| No. of MR exams        |         |           |         |
| 1                      | 4       | 28        | 32      |
| 2                      | 4       | 6         | 10      |
| 3                      | 5       | 6         | 11      |
| 4                      | 0       | 1         | 1       |
| 5                      | 1       | 0         | 1       |
| 6                      | 1       | 1         | 2       |
| Total                  | 38      | 68        | 106     |

*In all patients (except one girl), MR examinations were performed either with or without sedation. MMD, moyamoya disease.

Table 3 Artifacts in sedated pediatric patients with MMD

| Sequence | Artifact (+) | Artifact (-) |
|----------|--------------|--------------|
| qDWI     | 0            | 38           |
| cDWI     | 5*           | 33           |

* One patient awoke from sedation during cDWI acquisition, which was counted as one artifact. cDWI, conventional diffusion-weighted MRI; MMD, moyamoya disease; qDWI, quiet diffusion-weighted MRI.

Fig. 2 A sedated 6-year-old boy with MMD. No artifact other than susceptibility is observed on (a) qDWI with b = 1000, whereas blurring is observed on (b) cDWI. The arrows indicate metal artifact due to STA-MCA anastomosis. cDWI, conventional diffusion-weighted MRI; MCA, middle cerebral artery; MMD, moyamoya disease; qDWI, quiet diffusion-weighted MRI; STA, superficial temporal artery.

without sedation. Fifty-three scans were performed in the order of qDWI followed by cDWI, and the remaining 53 scans were obtained in reverse order.

Artifacts in sedated patients
No artifacts were observed on qDWI but were evident in four scans in which blurring and ghosting were observed on cDWI (P = .04, Table 3). One patient awoke from sedation during cDWI acquisition, and no cDWI was obtained. Fig. 2 shows qDWI and cDWI of a representative patient. The ICC value on qDWI was not calculated because no artifact was found. The ICC value on cDWI was 1.00 because there was no disagreement.

Artifacts in unsedated patients
Three scans showed ring-shaped, ‘crumpled’, or blurring artifacts on qDWI, whereas two scans showed artifacts on cDWI (P = .65, Table 4). Representative images are presented in Figs. 3 and 4. On qDWI, the ICC value was 0.88 (95% confidence interval [CI]: 0.82–0.92). On cDWI, the ICC value was 0.95 (95% CI: 0.92–0.97).

Restricted diffusion in sedated and in unsedated patients
qDWI revealed three cases of restricted diffusion, whereas two cases were found on cDWI (P = .66, Supplementary
Table 1. Representative images are shown in Fig. 5 and Supplementary Fig. 2. On qDWI, the ICC value was 0.88 (95% CI: 0.84–0.92). On cDWI, the ICC value was 0.86 (95% CI: 0.80–0.90).

Separate analysis of examinations in MAGNETOM Prisma and MAGNETOM Skyra
Fifty-seven MR examinations were performed in MAGNETOM Prisma, and there were 21 scans for sedated patients.
and 36 scans for unsedated patients. In sedated patients, no artifacts were observed on qDWI, whereas two scans showed artifacts on cDWI \((P = .15)\). In unsedated patients, no artifacts were observed on qDWI but were evident in one scan in which blurring was observed on cDWI \((P = .31)\). One patient demonstrated restricted diffusion on both qDWI and cDWI \((P = 1.00)\).

Forty-nine MR examinations were performed in MAGNETOM Skyra, and there were 17 scans of sedated patients and 32 scans of unsedated patients. In sedated patients, no artifacts were observed on qDWI, while two scans showed artifacts on cDWI \((P = .13)\). One patient awoke from sedation during cDWI acquisition, and no cDWI was obtained. In unsedated patients, three scans showed ring-shaped, crumpled, or blurring artifacts on qDWI, whereas one scan showed ghosting on cDWI \((P = .30)\). Two patients demonstrated restricted diffusion on qDWI, while one patient showed restricted diffusion on cDWI \((P = .57)\).

**Quantitative evaluation of acoustic noise and SNR**

For MAGNETOM Prisma, acoustic noise of qDWI and cDWI was 71.0 dB(A) and 75.1 dB(A), respectively. For MAGNETOM Skyra, acoustic noise of qDWI and cDWI was 79.3 dB(A) and 84.8 dB(A), respectively. Fig. 6 shows SNR maps of qDWI and cDWI. The SNR values (mean ± standard deviation) are shown in Supplementary Tables 2 and 3.

**Discussion**

We evaluated the suitability of qDWI in comparison with cDWI for pediatric patients with MMD. In sedated children, qDWI showed significantly fewer artifacts than did cDWI. For unsedated patients, no significant difference in artifacts was found between the two sequences. qDWI and cDWI performed equally in detecting restricted diffusion. When the examinations in MAGNETOM Prisma and MAGNETOM Skyra were separately analyzed, there were
no statistically significant differences. Thus, the present study demonstrated the advantage of qDWI over cDWI at 3T for sedated pediatric patients with MMD. One patient awoke from sedation during cDWI scanning, and no patient awoke from sedation during qDWI acquisition. The reduction in acoustic noise by 4.1–5.5 dB(A) in qDWI corresponds to a reduction of 38%–47% in sound pressure compared with cDWI, leading to patient comfort during scanning. We confirmed that the values of the peripheral ROIs were higher than those of the central ROIs on all SNR maps, which was attributed to phased-array coil sensitivity profiles. We also found that cDWI showed higher SNR than qDWI, and qDWI and cDWI had a similar tendency.

The blurring and ghosting artifacts observed on cDWI were caused by head motion. These artifacts were observed in only a few of the images. Motion artifact on MRI degrades the image quality and can interfere with interpretation. It also causes misalignment of data and induces noise in the images. In the presence of macroscopic tissue motion due to head movement, spins undergo large deviations that yield large phase shifts. Since the amplitude and direction of these motions are not identical, the distribution of phase shifts over time causes ghosting along the phase-encoding direction. qDWI is equipped with motion correction because readout-segmented echo-planar imaging is a multi-shot sequence and is sensitive to motion. However, it is difficult to eliminate motion artifact. A previous study reported ring-shaped artifacts associated with patient movement or chemical shift on qDWI obtained on a 1.5T MR unit. In the present study, ring-shaped and blurring artifacts were seen simultaneously on qDWI, so we consider that the ring-shaped artifact was due to head motion. A crumpled artifact was observed on qDWI, and ghosting was found on cDWI in the same Fig. 5 An unsedated 13-year-old girl with MMD. A tiny area of restricted diffusion (arrows) is detectable in the left frontal lobe on (a) qDWI with $b = 1000$ but is hard to detect on (b) cDWI with $b = 1000$. cDWI, conventional diffusion-weighted MRI; MMD, moyamoya disease; qDWI, quiet diffusion-weighted MRI.

Fig. 6 SNR maps of qDWI (a, c, e, g) and cDWI (b, d, f, h) are shown. SNR maps of $b = 0$ are shown in the upper row (a, b, c, d) and those of $b = 1000$ are shown in the lower row (e, f, g, h). SNR maps acquired at MAGNETOM Skyra (a, b, e, f) and those at MAGNETOM Prisma (c, d, g, h) are shown. cDWI shows higher SNR compared with qDWI probably due to the number of averages of 5. cDWI, conventional diffusion-weighted MRI; qDWI, quiet diffusion-weighted MRI.
examination. Therefore, we consider that the crumpled artifact is causally related to head motion. The artifact rates of the two sequences were similar in unsedated patients and that of qDWI was lower than that of cDWI in sedated patients, which might mean that the motion correction of qDWI was useful, as sedation suppressed coarse movements and kept them to a minimum.

In qDWI, no averaging was applied, whereas cDWI was acquired with five averages to adjust the scan time of each DWI sequence. cDWI shows higher SNR compared with qDWI probably due to the number of averages of 5. However, qDWI revealed restricted diffusion comparable to cDWI. With the exception of TOF-MRA, quiet sequences have been reported for SWI, T2WI, FLAIR, and T1WI using fast low-angle shot or pointwise encoding time reduction with radial acquisition, some of which we have included in our imaging protocol for pediatric patients with MMD. TOF-MRA is usually performed preferentially to detect progressive steno-occlusion of intracranial vessels and the development of collateral vasculature. However, the most appropriate order in which to perform qDWI among the pediatric MR sequences is yet to be determined. The optimal order of qDWI has not been investigated from the viewpoint of artifacts associated with acoustic noise and scan time.

Our study has several limitations. First, we have to take into consideration possible influences due to the overlap of the patients and possible effects from using two different MRI machines. However, only one patient, who had six examinations under sedation (four in MAGNETOM Prisma and two in MAGNETOM Skyra), showed artifacts on cDWI once in MAGNETOM Prisma and once in MAGNETOM Skyra, and no artifacts were observed in the remaining four examinations. No other patients demonstrated artifacts more than once. Also, no patients showed restricted diffusion more than once (Fig. 1 and Table 2). Second, the detectability of qDWI for restricted diffusion was not fully examined because lesions with restricted diffusion were detected in only three patients. However, as MMD is one of the most common cerebrovascular diseases for the pediatric population, the small number of lesions is considered inevitable. Third, cDWI with shorter scan time, which might be resistant to motion artifact, was not evaluated for patients. Improved SNR by using deep learning reconstruction has a potential to reduce scan time of cDWI. Finally, only one type of disease was studied in a relatively limited number of patients, and we observed a small number of artifacts.

Conclusion

qDWI induced fewer artifacts compared with cDWI in sedated pediatric patients with MMD, and similar frequencies of artifacts were induced by qDWI and cDWI in unsedated pediatric patients with MMD. qDWI demonstrated restricted diffusion comparable to cDWI.

Funding

This work was supported by JSPS KAKENHI Grant Number JP18K07711 and 19K17266.

Acknowledgments

We are grateful to Yuta Urushibata, MSci, from Siemens Healthcare K.K. for helpful discussion.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Supplementary Materials

Supplementary Tables 1–3 and Figs. 1–2 are available online.

Supplementary Table 1

Restricted diffusion in sedated and in unsedated patients with MMD.

Supplementary Table 2

SNR values of b = 0.

Supplementary Table 3

SNR values of b = 1000.

Supplementary Fig. 1

Eight circular ROIs of the same size were placed. Four ROIs were placed in the center, which yielded the central ROI. The other ROIs were placed on the four edges of the top, bottom, left and right sides, which yielded the peripheral ROI.

Supplementary Fig. 2

A sedated 2-year-old boy with MMD. qDWI with b = 1000 (a) with corresponding apparent diffusion coefficient map (c) and cDWI sequence (b, d), showing a tiny area of restricted diffusion (arrows) in the right frontal lobe.

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