Magn Reson Med Sci
doi:10.2463/mrms.mp.2022-0112 Published Online: March 16, 2023

MAJOR PAPER

Thin-slice Two-dimensional T2-weighted Imaging with Deep Learning-based Reconstruction: Improved Lesion Detection in the Brain of Patients with Multiple Sclerosis

Masatoshi Iwamura[1,2], Satoru Ide[3*], Kenya Sato[2], Akihisa Kakuta[2], Soichiro Tatsuo[1], Atsushi Nozaki[4], Tetsuya Wakayama[4], Tatsuya Ueno[5], Rie Haga[5], Misako Kakizaki[2], Yoko Yokoyama[2], Ryoichi Yamauchi[2], Fumiyasu Tsushima[1], Koichi Shibutani[2], Masahiko Tomiyama[6], and Shingo Kakeda[1]

Purpose: Brain MRI with high spatial resolution allows for a more detailed delineation of multiple sclerosis (MS) lesions. The recently developed deep learning-based reconstruction (DLR) technique enables image denoising with sharp edges and reduced artifacts, which improves the image quality of thin-slice 2D MRI. We, therefore, assessed the diagnostic value of 1 mm-slice-thickness 2D T2-weighted imaging (T2WI) with DLR (1 mm T2WI with DLR) compared with conventional MRI for identifying MS lesions.

Methods: Conventional MRI (5 mm T2WI, 2D and 3D fluid-attenuated inversion recovery) and 1 mm T2WI with DLR (imaging time: 7 minutes) were performed in 42 MS patients. For lesion detection, two neuroradiologists counted the MS lesions in two reading sessions (conventional MRI interpretation with 5 mm T2WI and MRI interpretations with 1 mm T2WI with DLR). The numbers of lesions per region category (cerebral hemisphere, basal ganglia, brain stem, cerebellar hemisphere) were then compared between the two reading sessions.

Results: For the detection of MS lesions by 2 neuroradiologists, the total number of detected MS lesions was significantly higher for MRI interpretation with 1 mm T2WI with DLR than for conventional MRI interpretation with 5 mm T2WI (765 lesions vs. 870 lesions at radiologist A, < 0.05). In particular, of the 33 lesions in the brain stem, radiologist A detected 21 (63.6%) additional lesions by 1 mm T2WI with DLR.

Conclusion: Using the DLR technique, whole-brain 1 mm T2WI can be performed in about 7 minutes, which is feasible for routine clinical practice. MRI with 1 mm T2WI with DLR enabled increased MS lesion detection, particularly in the brain stem.

Keywords: *brain, deep learning-based reconstruction, magnetic resonance imaging, multiple sclerosis*

Introduction

Multiple sclerosis (MS) is an inflammatory demyelinating disease of the central nervous system.[1] Brain MRI, including T2-weighted imaging (T2WI), fluid-attenuated inversion recovery (FLAIR) imaging, and T1-weighted imaging (T1WI) with and without gadolinium-based contrast enhancement, yield important information for diagnosing MS, understanding its natural history, and assessing the efficacy of treatment. A previous investigator showed that the number of lesions detected early in the disease process is associated with future relapse, disability accumulation, and cognitive

[1]Department of Radiology, Hirosaki University Graduate School of Medicine, Hirosaki, Aomori, Japan
[2]Department of Radiology, Aomori Prefectural Central Hospital, Aomori, Aomori, Japan
[3]Department of Radiology, University of Occupational and Environmental Health, School of Medicine, Kitakyushu, Fukuoka, Japan
[4]MR Application and Workflow, GE Healthcare, Tokyo, Japan
[5]Department of Neurology, Aomori Prefectural Central Hospital, Aomori, Aomori, Japan
[6]Department of Neurology, Hirosaki University Graduate School of Medicine, Hirosaki, Aomori, Japan

*Corresponding author: Department of Radiology, University of Occupational and Environmental Health, School of Medicine, 1-1, Iseigaoka, Yahatanishi-ku, Kitakyushu, Fukuoka 807-8555, Japan. Phone: +81-93-691-7450, Fax: +81-93-692-0249, E-mail: s-ide@med.uoeh-u.ac.jp

Received: September 8, 2022 | Accepted: February 10, 2023

impairments.[2] Therefore, an MRI sequence with a high sensitivity for detecting small MS lesions is desired.

Brain MRI with high spatial resolution allows for a more detailed delineation of MS lesions. The recently developed 3D FLAIR technique using 1 mm cubic voxels is useful for evaluating small MS lesions.[3,4] However, while FLAIR techniques have been widely used in the evaluation of MS lesions, FLAIR has some pitfalls. Okuda et al. reported that MS lesions were sometime obscured on FLAIR due to insufficient lesion contrast.[5] Especially, MS lesions in basal ganglia and brain stem, which were clearly depicted on T2WI, were difficult to identify on FLAIR. Therefore, for improved MS lesion detection, high-spatial-resolution T2WI is required. Fujita et al. reported 3D quantitative synthetic MRI, which enables the simultaneous quantification of T1WI, T2WI, and proton attenuation of the whole brain in 3D with a small section thickness.[6] However, they also found that the overall diagnostic image quality of synthetic T2WI was inferior to that of conventional T2WI. Thus, achieving high-spatial-resolution T2WI with adequate image contrast remains challenging.

Achieving high-spatial-resolution MRI is limited by the trade-off between image noise and spatial resolution. The recently developed deep learning-based reconstruction (DLR) approach enables image denoising with sharp edges and reduced artifacts, which improves the image quality of thin-slice MRI.[7–9] Kim et al. applied DLR to the 2D spin echo sequence, showing that, for the postoperative evaluation of pituitary adenoma, 1 mm-slice-thickness MRI with DLR showed greater diagnostic performance than conventional MRI with a 3 mm slice thickness.[10,11] Therefore, we hypothesized that the detection of MS lesions could be also improved by the addition of 1 mm-slice-thickness 2D T2WI with DLR (1 mm T2WI with DLR) to routine MRI. We, therefore, compared the diagnostic value of 1 mm T2WI with DLR for identifying MS lesions with that of conventional MRI interpretation with conventional T2WI (5 mm T2WI).

Materials and Methods

The Institutional Review Board approved this retrospective study and waived the need for informed consent for patients with MS. From all healthy volunteers, written informed consent was obtained.

Patients

The study population included 43 patients with MS (13 men, 30 women; median, 44 years old; age range, 19–87 years old) who underwent our standard brain MRI protocol (5 mm T2WI, T1WI, 2D and 3D FLAIR, and contrast-enhanced T1WI), including 1 mm T2WI with DLR. Of 43 patients, all had undergone 2D FLAIR imaging, and 3D FLAIR imaging was performed in 42 patients. The patients had chronic, clinically definite[12] MS (secondary progressive in 6 patients and relapsing-remitting in 37 patients; mean disease duration, 75.0 months). MS was diagnosed by 2 of the authors (T.U, with 18 years of experience in movement disorders and M.T. with 30 years of experience in neurology).

MRI

All studies were performed with a 3T MRI system (Discovery MR750w 3.0T Wide Bore MRI; GE Healthcare, Tokyo, Japan). The acquisition parameters of the sequences are shown in Table 1. To reconstruct 1 mm T2WI, a vendor-supplied product version of a deep learning algorithm (AIR Recon DL; GE Healthcare) was used.[10] This software program uses a deep convolutional network embedded in the image reconstruction pipeline. The network replaces traditional k-space apodization windows and postprocessing filters and provides a sharp denoised image with reduced Gibbs ringing artifacts. The software program accepts a noise reduction factor among low, mid, and high to accommodate user preferences, and a high noise reduction factor was used in this study. The algorithm was integrated into the system vendor's reconstruction pipeline, such that two sets (original and deep learning reconstructed) of images were generated from a single set of raw k-space data.

Image analyses

To compare MRI interpretation with 5 mm T2WI and with 1 mm T2WI with DLR, an observer performance study was performed by 2 neuroradiologists (Radiologist A: S.I and Radiologist B: M.I, with 15 and 7 years of experience in neuroradiology, respectively). The radiologists were informed of (a) the MS patients included in the study, (b) the task of this study: consisting of 2 phases for each individual MS lesion: lesion detection and classification regarding the region category (periventricular or deep white matter [WM], juxtacortical, deep gray matter [GM], brain stem, and cerebellar regions), (c) the fact that lesions larger than 2 mm in diameter were to be counted, and (d) the fact that hyperintense MS lesions on T2WI and FLAIR and hypointense lesions on T1WI were to be counted. For the juxtacortical MS lesions, according to the previous study,[13] the radiologists further classified MS lesions into three patterns according to their anatomical locations: (a) subcortical WM lesions involving the subcortical WM alone; (b) intracortical lesions involving the GM alone; (c) mixed GM and subcortical WM lesions involving both subcortical WM and GM.

At the first reading session, conventional MR images (5 mm T2WI, T1WI, 2D and/or 3D FLAIR, and CE spin-echo imaging) were shown for conventional interpretation, and the neuroradiologists detected the MS lesions and classified them according to the region category. In the second reading session, the neuroradiologists reviewed the 1 mm T2WI with DLR as well as the conventional MR images, except for conventional 5 mm T2WI. Each observer performed the second reading session eight weeks after the first reading session.

Table 1 MR imaging acquisition parameters

	T1WI	T2WI	2D FLAIR	3D FLAIR	1 mm T2WI with DLR	1 mm T2WI with PI	1 mm T2WI without PI
Acuisition plane	2D axial	2D axial	2D axial	3D sagittal	2D axial	2D axial	2D axial
TR (ms)	440	5674	9000	9000	11600	11600	11600c
TE (ms)	12	99.4	122.6	105	97.4	97.4	97.4
TI (ms)	NA	NA	2470.8	2457	NA	NA	NA
ETL	NA	14	14	160	24	24	24
Flip angle (degrees)	90	111	110	90	160	160	160
BW (kHz)	20.8	31.2	25	50	62.5	62.5	62.5
FOV (cm)	22×18.7	22×18.7	22×18.7	22×20.9	22×22	22×22	22×22
Matrix size	512×224	512×256	320×224	256×256	220×220	220×220	220×220
ST (mm)	5	5	5	0.7	1	1	1
NEX	2	1	1	1	1	1	1
AF (ARC)	NA	NA	2	2	2	2	NA
CS-HSF	NA	NA	NA	1.15	NA	NA	NA
AT	5 min 45 sec	1 min 36 sec	2 min 33 sec	6 min 4 sec	6 min 47 sec	6 min 47 sec	10 min 38 sec

AF, acceleration factor; ARC, auto calibrating reconstruction for cartesian imaging; AT, acquisition time; BW, band width; CS-HSF, compressed sensing HyperSense factor; DLR, deep learning-based MRI reconstruction; ETL, echo train length; FLAIR, fluid-attenuated inversion recovery; NA, not applicable; NEX, number of excitation; PI, parallel imaging; ST, slice thickness; TI, inversion time; T1W1, T1-weighted imaging; T2WI, T2-weighted imaging.

Each detected lesion was retrospectively validated using all available imaging data by another two neuroradiologists (S.K. and T.F, with 28 and 20 years of experience in neuroradiology, respectively) in consensus to exclude false-positive lesions.

Comparing 1 mm T2WI with and without DLR

On the 1 mm T2WI with and without DLR, two experienced neuroradiologists (S.K and T.F) graded the visibility of the MS lesions. The visibility of the MS lesion was defined by the demarcation between the MS lesion and adjacent brain parenchyma. The visibility of the MS lesion was graded as follows: grade 2, MS lesion completely identified as a structure with different signal intensity (SI) relative to adjacent brain parenchyma; grade 1, MS lesion identified, but it is difficult to differentiate between MS lesion and brain parenchyma (background noise); grade 0, MS lesion not identified (MS lesion is not able to differentiate from background noise).

As a quantitative evaluation, for the largest MS lesion in the 42 patients, the SNR and contrast-to-noise ratio (CNR) between the lesion and brain parenchyma were calculated for 1 mm T2WI with and without DLR according to the previous studies.[10] ROIs were placed in the background, brain parenchyma, and MS lesions. The standard deviation of the background ROI SI was considered noise. The mean SI was measured in each annotated ROI. The ROI of brain parenchyma was mainly located in the WM to avoid structures such as blood vessels. The SNR of the MS lesions was calculated as the mean SI of the MS lesions by noise. The CNR between the MS lesions and brain parenchyma was defined as the absolute difference in mean SI between the two tissues divided by the noise.

The evaluation of artifacts

Furthermore, according to the region category (brain stem/cerebellum, deep GM, cerebrum), two neuroradiologists (S.K and T.F) evaluated artifacts on 1 mm T2WI with and without DLR using the following four categories: 4 = no visible artifacts, 3 = minimal artifacts that did not interfere with the diagnostic quality, 2 = moderate artifacts sufficient to interfere with the diagnostic quality, and 1 = heavy artifacts resulting in nondiagnostic study. When an artifact was presented, the neuroradiologists were asked to indicate the locations and characteristics of artifacts (e.g. unknown, patient's motion artifact, etc.).

Healthy volunteer study: The comparison between 1 mm T2WI obtained with and without the parallel imaging technique

For artifacts rated as minimal or moderate (see Table 2), the neuroradiologists scored their mechanism as unknown (see results in *The evaluation of artifacts*). Therefore, to determine whether or not the parallel imaging technique might affect these artifacts, we performed a comparison study between 1 mm T2WI with DLR with and without the parallel imaging technique using three healthy volunteers. For 1 mm

Table 2 The grading category of the artifacts by two radiologists

	Grading category of the artifacts			
	4	3	2	1
Patients (n = 42)	12	20	10	0
Regions				
Brain stem or cerebellum (n = 42)	13	19	10	0
Deep gray matter (n = 42)	32	10	0	0
Cerebrum (n = 42)	35	7	0	0

4 = no visible artifact, 3 = minimal artifact that did not interfere with diagnostic quality, 2 = moderate artifact sufficient to interfere with diagnostic quality, and 1 = heavy artifact resulting in nondiagnostic study.

Table 3 Lesion detections by the MRI interpretations with conventional MRI and with 1 mm T2WI with DLR

	Radiologist A		Radiologist B	
	With conventional MRI	With 1 mm T2WI with DLR	With conventional MRI	With 1 mm T2WI with DLR
Periventricular or deep WM	565	602	551	602
Juxtacortical region				
GM alone	11	11	10	10
Subcortical WM and GM.	20	23	21	25
Subcortical WM alone	113	135	97	117
Deep GM	33	48	32	44
Brain stem	12	33	13	33
Cerebellum	11	18	11	18
Total	765	870	735	849

DLR, deep learning-based MRI reconstruction; GM, gray matter; T2WI, T2-weighted imaging; WM, white matter.

T2WI with DLR with and without the parallel imaging technique (auto calibrating reconstruction for cartesian imaging[ARC]), the pulse sequences are shown in Table 1.

Statistical analyses

All statistical analyses were performed on the R program version 3.3.0 (http://www.r-project.org/; R Foundation for Statistical Computing, Vienna, Austria). The Chi-squared test was used to compare the lesion count between the MRI interpretations with 5 mm T2WI and with 1 mm T2WI with DLR. The statistical significance of differences in three qua-litative criteria between the two sequences was tested using the signed rank's test. Interobserver reliabilities were calculated as Cohen's kappa coefficient. The strength of agreement was considered fair for Kappa values of 0.21–0.40, moderate for Kappa values of 0.41–0.60, good for Kappa values of 0.61–0.80, and excellent for Kappa values > 0.80. For the SNR and CNR, a *P* value for comparison between the 1 mm T2WI with and without DLR was calculated using paired *t* test.

Results

The comparison between MRI interpretation with 5 mm T2WI and with 1 mm T2WI with DLR

Regarding the detection of the MS lesions, the results obtained by the two neuroradiologists are summarized in Table 3. The total number of detected MS lesions was significantly higher for MRI interpretation with 1 mm T2WI with DLR than for MRI interpretation with 5 mm T2WI (870 lesions vs. 765 lesions, < 0.05). For radiologists A and B, MRI interpretation with 1 mm T2WI with DLR identified 105/870 (12.1%) and 114/849 (13.4%) additional lesions that were not seen on conventional MR images, respectively. In particular, radiologists A and B detected 21 (63.6%) and 20 (60.6%) additional lesions in the brain stem by 1 mm T2WI with DLR, respectively (Fig. 1). The use of 1 mm T2WI with DLR improved the lesion detections in periventricular and deep WM, which resulted in 1 mm T2WI with DLR allowing the radiologists to discriminate small MS

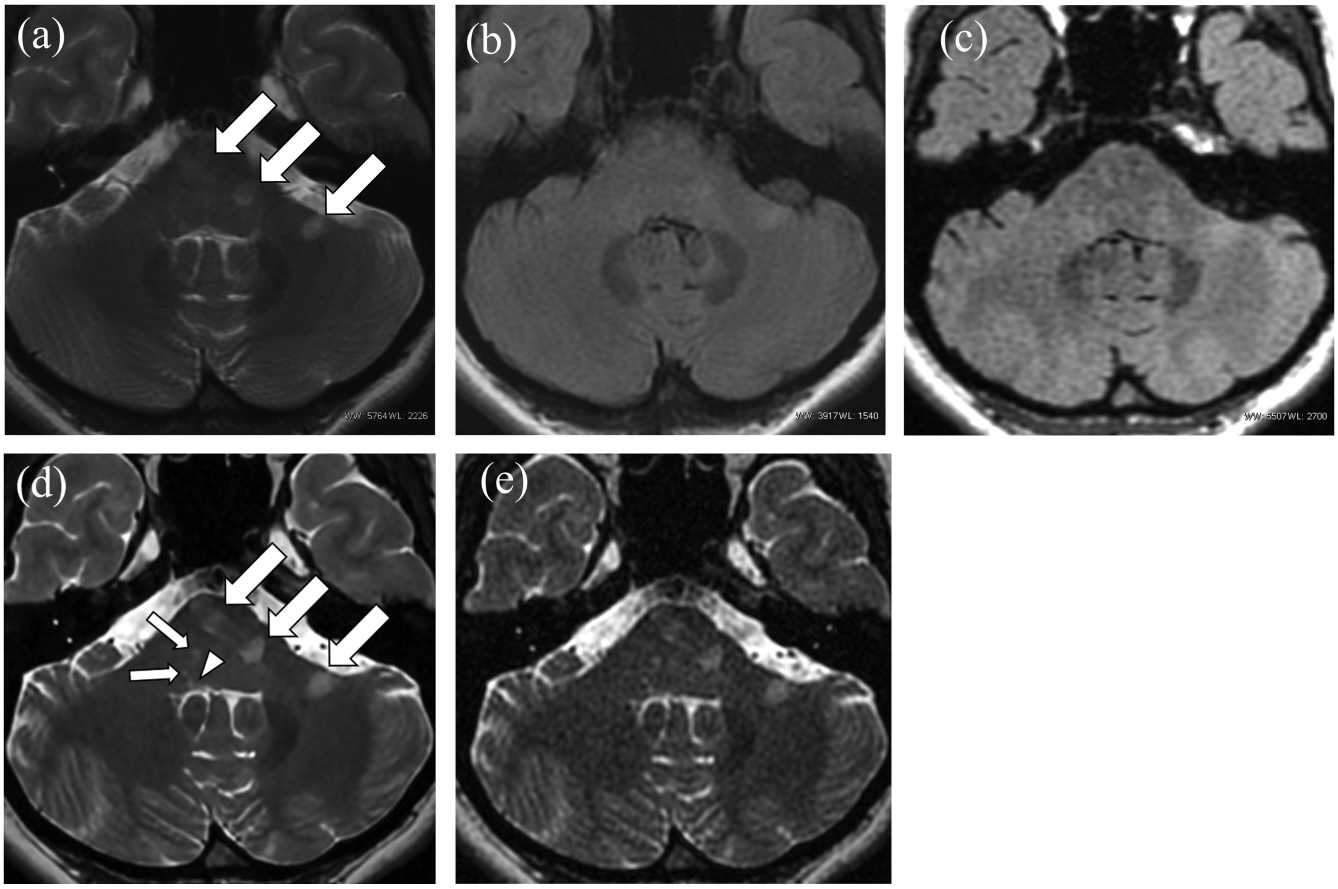

Fig. 1 Relatively large MS lesions (large arrows) can be seen on both 5 mm T2WI (**a**) and 1 mm T2WI with DLR (**d**). In contrast, small MS lesions might have been missed on 5 mm T2WI (**a**), 2D FLAIR (**b**), and 3D FLAIR (**c**), although 1 mm T2WI with DLR (**d**) showed good delineation of these lesions (small arrows). With regard to the visibility of MS lesions, 1 mm T2WI with DLR (**d**) was superior to 1 mm T2WI without DLR (**e**); the lesion (arrowhead) on the 1 mm T2WI with DLR (**d**) can be accurately differentiated from background noise, but not on the 1 mm T2WI without DLR (**e**). DLR, deep learning-based reconstruction; FLAIR, fluid-attenuated inversion recovery; MS, multiple sclerosis; T2WI, T2-weighted imaging.

lesions from overlapping hyperintensity due to large and conflating MS lesions (Fig. 2).

The Kappa values for interobserver variability between the 2 radiologists were 0.7183 for the first reading session and 0.6862 for the second reading session; these values indicated with "good" and "good" interobserver agreement, respectively.

The comparison between 1 mm T2WI with and without DLR

The visibility of MS lesions was greater on the 1 mm T2WI with DLR images than on the without DLR images (< 0.01) (Table 4) (Fig. 1d and 1e). Of the 870 MS lesions, by reviewing by Radilogist A, the 1 mm T2WI with DLR could detect 80 (9.1%) MS lesions (grade 0) that were not seen on the 1 mm T2WI without DLR. The Kappa value for interobserver variability between the 2 radiologists was 0.7058; the value indicated with "good" interobserver agreement, respectively.

The results of SNR and CNR measurements for 42 MS lesions are shown in Table 5. The SNR of the MS lesion on 1 mm MRI scans was increased by a factor of 2.3 (95% confidence interval [CI]: 2.3, 2.4) by applying DLR (mean SNR: 132.9 with 1 mm T2WI with DLR vs. 57.1 with 1 mm T2WI without DLR, < 0.01). The CNR between the MS lesion and brain parenchyma was increased by a factor of 2.3 (mean CNR: 52.8 with 1 mm T2WI with DLR vs. 22.5 with 1 mm T2WI without DLR, < 0.01).

The evaluation of artifacts

Regarding the evaluation of artifacts on 1 mm T2WI with DLR, 12 (27.9%) of the 43 patients were rated as 4 (no visible artifacts), 21 (48.8%) as 3 (minimal artifacts), and 10 (23.3%) as 2 (moderate artifacts), with none rated as 1 (heavy artifacts) (Table 2). All of the artifacts rated as 2 (moderate artifacts) were observed in brain stem. All artifacts were seen on both 1 mm T2WI both with DLR and without DLR (Fig. 3).

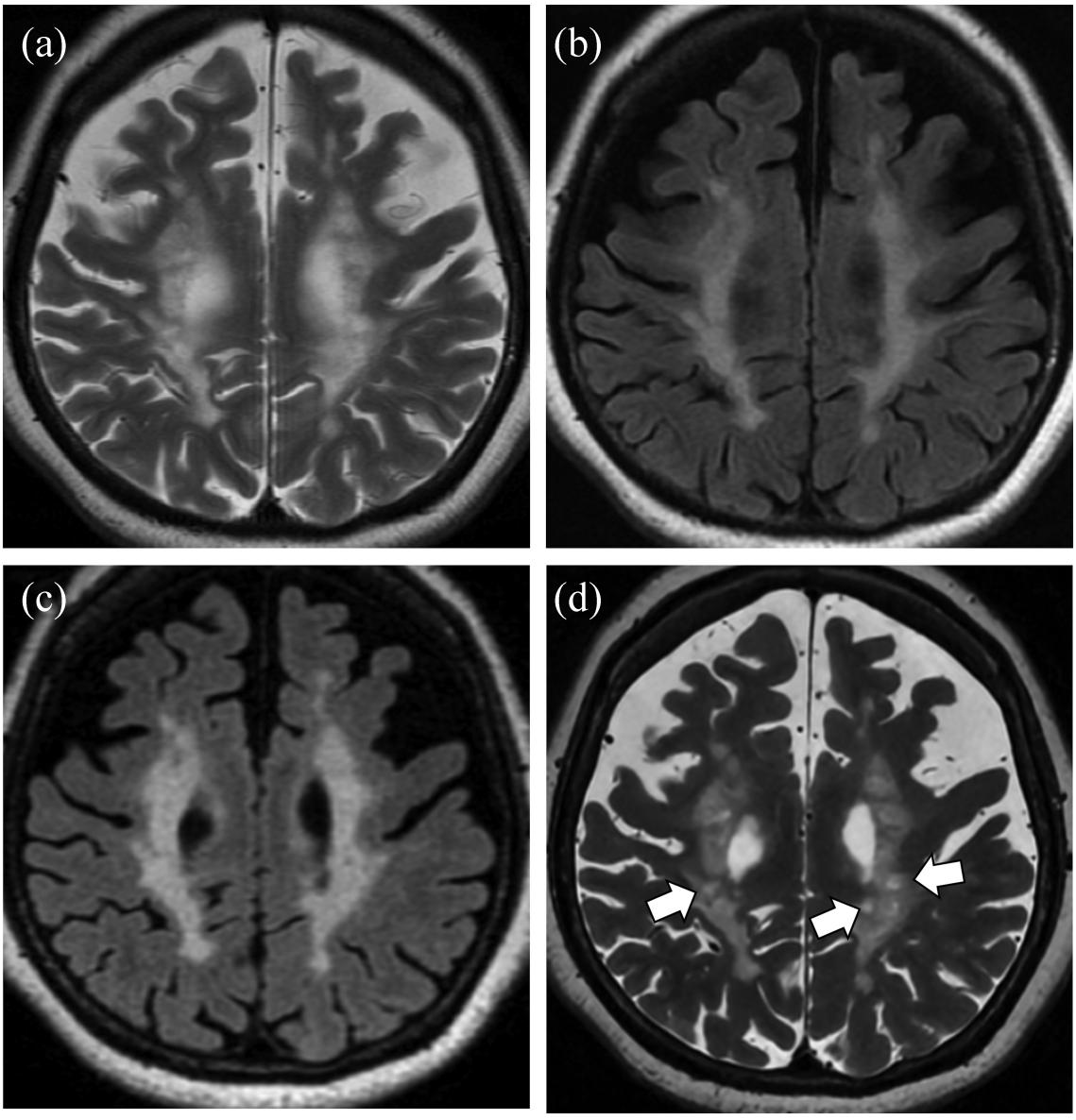

Fig. 2 1 mm T2WI (**a**), 2D FLAIR (**b**), and 3D FLAIR (**c**) show diffuse hyper signal intensity due to the large and conflating MS lesions in the periventricular and deep WM. In contrast, small MS lesions (arrows) in the periventricular and deep WM can be seen on 1 mm T2WI with deep learning-based reconstruction (**d**) by discriminating the lesions from overlapping high-intensity areas due to large and conflating lesions. FLAIR, fluid-attenuated inversion recovery; MS, multiple sclerosis; T2WI, T2-weighted imaging; WM, white matter.

Of the 37 artifacts rated as 3 (minimal artifacts), 20 (46.5%), 10 (23.3%), and 7 (16.3%) were seen in the brain stem, deep GM, and cerebrum, respectively. For artifacts rated as minimal or moderate, the neuroradiologists scored their mechanism as unknown.

Healthy volunteer study: The comparison between 1 mm T2WI with DLR obtained with and without the parallel imaging technique

For the evaluation of artifacts generated in three healthy volunteers, two of the volunteers showed artifacts in the brain stem. On comparing 1 mm T2WI with DLR obtained with and without the parallel imaging technique, these artifacts were only observed on 1 mm T2WI with the parallel imaging technique (Fig. 4).

Discussion

To our knowledge, no studies have assessed the usefulness of thin slice T2WI with DLR for the evaluation of MS lesions. Achieving 1 mm T2WI in routine clinical practice is challenging because of the inevitable trade-off between the imaging time and SNR, as well as between spatial resolution and SNR. In this study, by leveraging both parallel imaging and

Table 4 Lesion visibility on 1 mm T2WI with and without DLR

	Radiologist A		Radiologist B	
	1 mm T2WI with DLR	1 mm T2WI without DLR	1 mm T2WI with DLR	1 mm T2WI without DLR
Grade 2	870 (100%)	586 (67.3%)	849 (100%)	544 (64.1%)
Grade 1	0	202 (23.4%)	0	226 (26.5%)
Grade 0	0	80 (9.1%)	0	79 (9.2%)

Data are the number of MS lesions with percentage in parentheses. DLR, deep learning-based reconstruction; T2WI, T2-weighted imaging.

Table 5 SNR and CNR measurements of 42 lesions

	1 mm T2WI without DLR	1 mm T2WI with DLR	1 mm T2WI with DLR/ 1 mm T2WI without DLR	*P* value
SNR	43.4 (52.5–34.3)	80.2 (94.2–66.2)	2.1 (2.4–1.8)	< 0.01
CNR	20.1 (23.7–16.5)	37.1 (41.5–32.7)	2.2 (2.5–1.8)	< 0.01

Data are means with 95% confidence intervals in parentheses. CNR, contrast-to-noise ratio; DLR, deep learning-based reconstruction; T2WI, T2-weighted imaging.

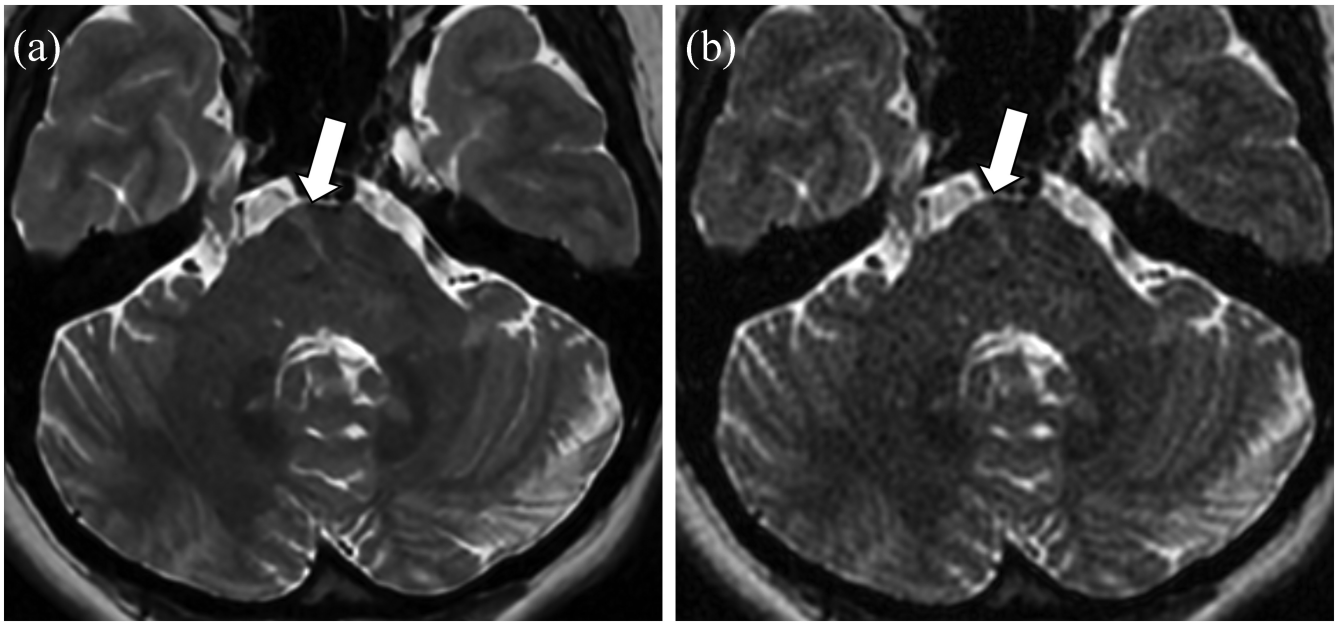

Fig. 3 An artifact can be seen on both 1 mm T2WI both with DLR (**a**) and without DLR (**b**) (arrows). DLR, deep learning-based reconstruction; T2WI, T2-weighted imaging.

DLR techniques, we achieved whole-brain T2WI with a spatial resolution of 1 mm slice thickness (acquisition time: 6 minutes 47 seconds). The 1 mm T2WI with DLR enabled us to detect more MS lesions than the conventional MRI protocol.

Few studies have evaluated the utility of DLR methods in clinical neuroimaging. Kidoh et al. showed that DLR reduces image noise while preserving the image quality obtained in a relatively short acquisition time.[9] However, they only evaluated the visualization of small brain anatomical structures, such as the hippocampus. Kim et al. found that 1 mm-slice-thickness MRI with DLR showed a greater diagnostic performance than 3 mm-slice-thickness MRI for identifying cavernous sinus invasion of pituitary adenoma.[10] Therefore, to our knowledge, this article is the first report of the clinical usefulness of 1 mm T2WI with DLR for the evaluation of MS lesions. Our findings are in line with previous neuroimaging studies.

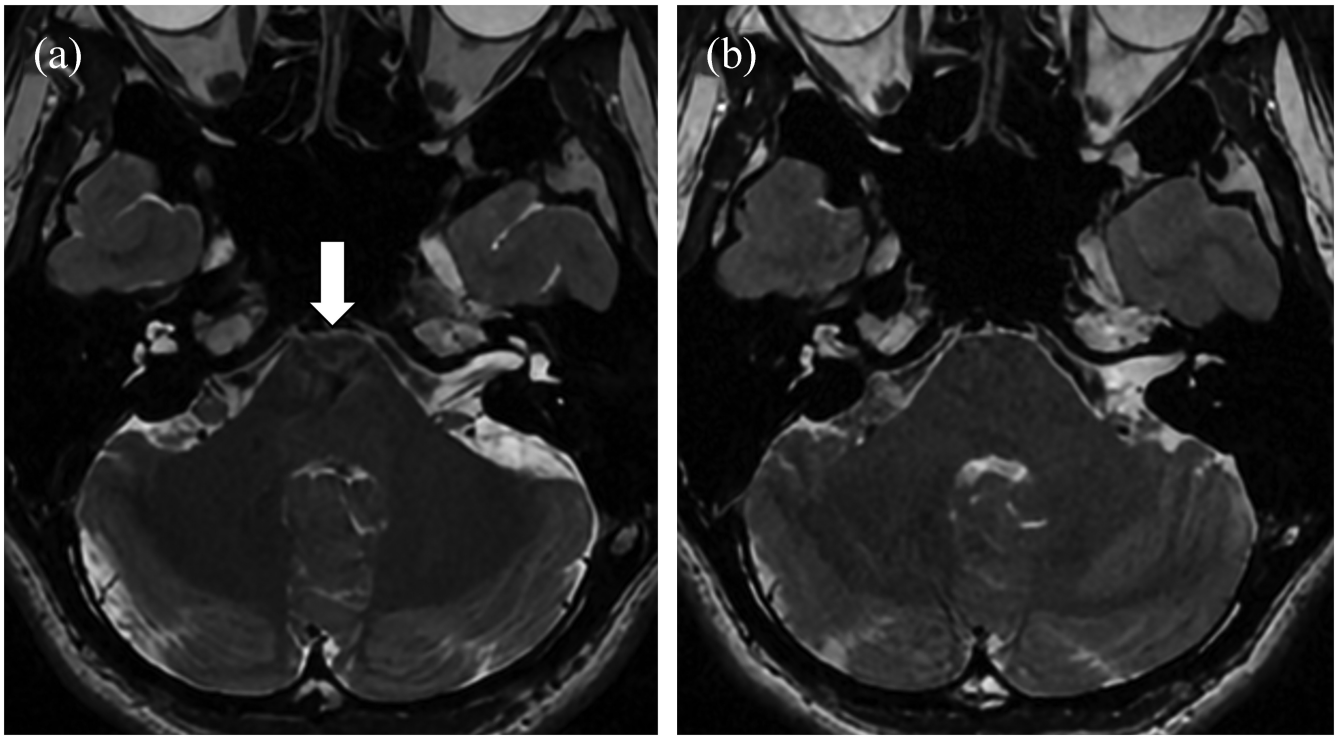

Fig. 4 1 mm T2WI with DLR with the PI technique (**a**) shows a moderate artifact in the brain stem (arrow) that is not seen on 1 mm T2WI with DLR without the PI technique (**b**). DLR, deep learning-based reconstruction; PI, parallel imaging; T2WI, T2-weighted imaging.

For small MS lesions, the improved detection with 1 mm T2WI with DLR may be largely due to its thin slice thickness, which reduces the partial volume effects. The use of 1 mm T2WI with DLR clearly improved the diagnostic accuracy for detecting MS lesions, especially in the brain stem. This result may also suggest that the 1 mm T2WI with DLR could detect the brain stem lesions that were not seen on the 3D FLAIR with thin-slice-thickness. Our assumption may be supported by a previous study, which reported that FLAIR images failed to demonstrate MS lesions located in the brain stem due to insufficient contrast.[5] Those investigators speculated that cerebrospinal fluid flow-related artifacts on FLAIR images may be a contributing factor to poor lesion conspicuity and detection of MS. Another possible explanation is that MS may have relaxation times similar to those of the adjacent brain parenchyma in the brain stem; anatomically, the brain stem is a structure that differs from that of WM. Furthermore, on FLAIR images, large and conflating lesions can obscure small MS lesions, particularly in the periventricular region and deep WM. We found that 1 mm T2WI with DLR allowed neuroradiologists to discriminate small MS lesions from overlapping high-intensity areas due to large and conflating MS lesions or ischemic changes (Fig. 2).

For detecting all MS lesions, 1 mm T2WI with DLR was significantly superior to 1 mm T2WI without DLR, suggesting that, for true-positive lesion detections, there were no lesions that were detrimentally affected by using DLR. Compared to the conventional denoising method using an image filter, DLR allows to remove only the noise and retain the detailed structural information without image blurring, which could provide thin slice 2D imaging with adequate image quality and SNR. This is also supported by our quantitative results using SNR and CNR. The DLR technique used in this study includes a deep convolutional neural network to reduce image noise and truncation artifacts while improving image sharpness.[10,14] Those effects helped to identify the small MS lesions and resulted in the better lesion detection on the thin slice T2W images in this study.

We found that artifacts were more frequently seen in the brain stem than in the other brain regions. van der Velde et al. reported that wrapping and ghosting artifacts were particularly prominent when DLR was used for late gadolinium enhancement imaging of myocardium.[15] However, in the present study, the artifact was also seen on the original images (1 mm T2WI without DLR), indicating that the artifact was not caused by the DLR process but rather propagated from the artifacts present in the original images (Fig. 3). Our comparison study of 1 mm T2WI with and without parallel imaging showed that the artifacts were only observed on images obtained with a acceleration factor of 2, suggesting that the main cause of the artifact may have been parallel imaging itself. Although a smaller reduction factor can be used to mitigate aliasing artifacts due to parallel imaging, this results in a longer acquisition time. Therefore, further optimization of these techniques might be

needed. Other techniques may also be applied to further shorten the scan time, including combining with techniques such as compressed sensing.[14] Importantly, in the present study, it was not difficult for observers to distinguish between artifacts and MS lesions by inspecting other MRI images (T1WI and FLAIR). Therefore, in clinical situations, issues may be mitigated if the existence of these artifacts is known in advance of reviewing images obtained via 1 mm T2WI with DLR.

This study was limited by its retrospective study design and the small number of patients. A prospective study with a larger sample size is needed to validate its diagnostic value and the impact on outcomes. The possibility of using other imaging modalities than T1WI, 5 mm T2WI, and FLAIR, such as double inversion recovery image, was not considered in this study. Our reference standard or the lesions was based on radiological consensus, especially on the finding by 1 mm T2WI with DLR. Therefore, the MS lesions, which were detected only by the 1 mm T2WI with DLR, might include false-positive lesions. The limitation of axial imaging in this study might have impeded the evaluation of lesions in the corpus callosum. Especially, 3D T2WI with DRL was not available. This suggests that our results included the MS lesions which were not identified only by the 1 mm T2WI with DLR. Therefore, it is important to note that these MR imaging (T2WI and FLAIR) yield different but complementary information. Our whole-brain 1 mm T2WI with DLR was performed in about 7 minutes, which may be relatively long for the daily practice. We can obtain 144 slices by our 1 mm T2WI protocol, which may be relatively large for covering whole-brain. Therefore, more recently, by reducing number of echo train length (20), flip angle (150 degrees), and number of acquisition slice (132 slices), we achieved 1 mm T2WI protocol with 5 minutes acquisition time. Advanced technology with artificial intelligence may make possible the image acquisition with a shorter image acquisition time.

Conclusion

MRI with 1 mm T2WI with DLR enabled increased MS lesion detection, particularly in the brain stem. By DLR, whole-brain 1 mm T2WI with DLR can be performed in about 7 minutes, which is feasible for routine clinical practice. Therefore, 1 mm T2WI with DLR may replace conventional 5 mm T2WI in routine MRI studies.

Conflicts of Interest

Atsushi Nozaki and Tetsuya Wakayama are employees of GE Healthcare Japan. The other authors declare that they have no conflicts of interest.

References

1. Brownlee WJ, Hardy TA, Fazekas F, Miller DH. Diagnosis of multiple sclerosis: progress and challenges. Lancet 2017; 389:1336–1346.
2. Lavery AM, Verhey LH, Waldman AT. Outcome measures in relapsing-remitting multiple sclerosis: capturing disability and disease progression in clinical trials. Mult Scler Int 2014; 2014: 262350.
3. Kakeda S, Korogi Y, Hiai Y, Ohnari N, Sato T, Hirai T. Pitfalls of 3D FLAIR brain imaging: a prospective comparison with 2D FLAIR. Acad Radiol 2012; 19:1225–1232.
4. Tan IL, Pouwels P, van Schijndel R, Adèr H, Manoliu R, Barkhof F. Isotropic 3D fast FLAIR imaging of the brain in multiple sclerosis patients: initial experience. Eur Radiol 2002; 12:559–567.
5. Okuda T, Korogi Y, Shigematsu Y, et al. Brain lesions: when should fluid-attenuated inversion-recovery sequences be used in MR evaluation? Radiology 1999; 212:793–798.
6. Fujita S, Yokoyama K, Hagiwara A, et al. 3D quantitative synthetic MRI in the evaluation of multiple sclerosis lesions. AJNR Am J Neuroradiol 2021; 42:471–478.
7. Chartrand G, Cheng PM, Vorontsov E, et al. Deep learning: a primer for radiologists. Radiographics 2017; 37:2113–2131.
8. Jiang D, Dou W, Vosters L, Xu X, Sun Y, Tan T. Denoising of 3D magnetic resonance images with multi-channel residual learning of convolutional neural network. Jpn J Radiol 2018; 36:566–574.
9. Kidoh M, Shinoda K, Kitajima M, et al. Deep learning based noise reduction for brain MR imaging: tests on phantoms and healthy volunteers. Magn Reson Med Sci 2020; 19:195–206.
10. Kim M, Kim HS, Kim HJ, et al. Thin-slice pituitary MRI with deep learning–based reconstruction: diagnostic performance in a postoperative setting. Radiology 2021; 298:114–122.
11. Kim M, Kim H, Park J, et al. Thin-slice pituitary MRI with deep learning–based reconstruction for preoperative prediction of cavernous sinus invasion by pituitary adenoma: A prospective study. AJNR Am J Neuroradiol 2022; 43:280–285.
12. Polman CH, Reingold SC, Edan G, et al. Diagnostic criteria for multiple sclerosis: 2005 revisions to the "McDonald Criteria". Ann Neurol 2005; 58:840–846.
13. Futatsuya K, Kakeda S, Yoneda T, et al. Juxtacortical lesions in multiple sclerosis: assessment of gray matter involvement using phase difference-enhanced imaging (PADRE). Magn Reson Med Sci 2016; 15:349-354.
14. Lustig M, Donoho D, Pauly JM. Sparse MRI: The application of compressed sensing for rapid MR imaging. Magn Reson Med 2007; 58:1182–1195.
15. van der Velde N, Hassing HC, Bakker BJ, et al. Improvement of late gadolinium enhancement image quality using a deep learning–based reconstruction algorithm and its influence on myocardial scar quantification. Eur Radiol 2021; 31:3846–3855.