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Improving Diagnostic Performance of MRI for Temporal Lobe Epilepsy With Deep Learning-Based Image Reconstruction in Patients With Suspected Focal Epilepsy

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Objective: To evaluate the diagnostic performance and image quality of 1.5-mm slice thickness MRI with deep learning-based image reconstruction (1.5-mm MRI + DLR) compared to routine 3-mm slice thickness MRI (routine MRI) and 1.5-mm slice thickness MRI without DLR (1.5-mm MRI without DLR) for evaluating temporal lobe epilepsy (TLE).

Materials and Methods: This retrospective study included 117 MR image sets comprising 1.5-mm MRI + DLR, 1.5-mm MRI without DLR, and routine MRI from 117 consecutive patients (mean age, 41 years; 61 female; 34 patients with TLE and 83 without TLE). Two neuroradiologists evaluated the presence of hippocampal or temporal lobe lesions, volume loss, signal abnormalities, loss of internal structure of the hippocampus, and lesion conspicuity in the temporal lobe. Reference standards for TLE were independently constructed by neurologists using clinical and radiological findings. Subjective image quality, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were analyzed. Performance in diagnosing TLE, lesion findings, and image quality were compared among the three protocols.

Results: The pooled sensitivity of 1.5-mm MRI + DLR (91.2%) for diagnosing TLE was higher than that of routine MRI (72.1%, $P < 0.001$). In the subgroup analysis, 1.5-mm MRI + DLR showed higher sensitivity for hippocampal lesions than routine MRI (92.7% vs. 75.0%, $P = 0.001$), with improved depiction of hippocampal T2 high signal intensity change ($P = 0.016$) and loss of internal structure ($P < 0.001$). However, the pooled specificity of 1.5-mm MRI + DLR (76.5%) was lower than that of routine MRI (89.2%, $P = 0.004$). Compared with 1.5-mm MRI without DLR, 1.5-mm MRI + DLR resulted in significantly improved pooled accuracy (91.2% vs. 73.1%, $P = 0.010$), image quality, SNR, and CNR (all, $P < 0.001$).

Conclusion: The use of 1.5-mm MRI + DLR enhanced the performance of MRI in diagnosing TLE, particularly in hippocampal evaluation, because of improved depiction of hippocampal abnormalities and enhanced image quality.

Keywords: Brain; Epilepsy; Temporal lobe; Magnetic resonance imaging; Deep learning

INTRODUCTION

Early surgical therapy for drug-resistant temporal lobe epilepsy (TLE) is highly effective, enabling patients to achieve seizure freedom and improve their quality of life [1]. Favorable outcomes have been observed in patients with hippocampal sclerosis identified on MRI, consistent with a seizure origin in the temporal lobe [2]. However, approximately 20%–40% of patients with focal epilepsy are "MRI-negative" on clinical MRI, indicating the absence of an identifiable lesion on 1.5T or 3T MRI [3-6]. Advanced imaging techniques using ultra-high-field MRI with high

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Korean Journal of Radiology
KJR

spatial resolution and an increased signal-to-noise ratio (SNR) can improve the visualization of smaller anatomical structures and subtle pathological findings [7,8]. Several studies have demonstrated that the conspicuity of internal hippocampal structures is improved using the high spatial resolution imaging provided by 7T MRI [9-12].

In the examination of TLE, turbo spin echo sequences with thin slices (i.e., 2 mm) are recommended for assessing the internal structure of the hippocampus, according to the Harmonized Neuroimaging of Epilepsy Structural Sequences (HARNESS-MRI) protocol proposed by the International League Against Epilepsy (ILAE) [13]. However, thin slices are associated with increased noise and scan time, resulting in lower SNR and image quality [14]. Deep learning-based image reconstruction (DLR) has recently been introduced to address these compromises related to spatial resolution. DLR learns to reconstruct images by recognizing patterns of low resolution and noise through training on previous data, thereby reconstructing only the ideal image [15]. Although previous studies have shown improved SNR and contrast-to-noise ratio (CNR) using DLR techniques [16-21], the utility of DLR for detecting abnormalities in the diagnosis of TLE has not been evaluated. We hypothesized that 1.5-mm slice-thickness oblique coronal 2D turbo spin echo T2-weighted imaging reconstructed with DLR (1.5-mm MRI + DLR) would be superior to routine 3-mm slice-thickness oblique coronal 2D turbo spin echo T2-weighted imaging (routine MRI) and 1.5-mm slice thickness MRI without DLR (1.5-mm MRI without DLR) in detecting focal lesions in patients with TLE.

Therefore, this study assessed the image quality and diagnostic performance of 1.5-mm MRI + DLR in comparison with routine MRI and 1.5-mm MRI without DLR to identify abnormalities in the evaluation of TLE.

MATERIALS AND METHODS

Study Population

This retrospective, single-institution study was approved by the Institutional Review Board of Asan Medical Center with a waiver for written informed consent (IRB No. 2022-0514). All data were managed according to Health Insurance Portability and Accountability Act standards and

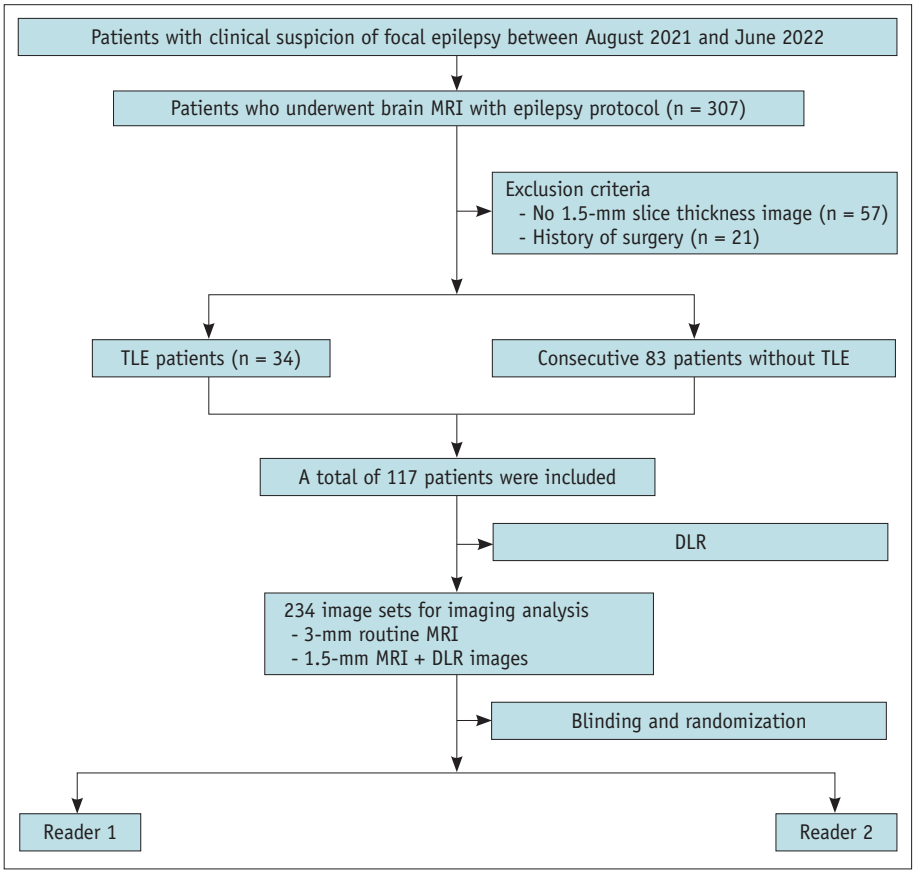

Fig. 1. Flow diagram of patient inclusion and image analysis. TLE = temporal lobe epilepsy, DLR = deep learning-based reconstruction

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were fully anonymized before being exported for research purposes. A flow diagram illustrating the patient inclusion process is shown in Figure 1. A total of 307 potentially eligible patients who underwent brain MRI with an epilepsy protocol due to clinical suspicion of focal epilepsy between August 2021 and June 2022 were retrospectively reviewed by an experienced neuroradiologist (J.E.P., with 10 years of experience in neuroradiology), who did not participate in image analysis. Exclusion criteria were as follows: 1) history of brain surgery (n = 21) and 2) a missing sequence of 1.5-mm slice imaging (n = 57). For the evaluation of diagnostic performance, both a disease-positive group (patients with TLE based on the reference standard) and a disease-negative group were included. Finally, a total of 117 patients (34 with TLE and 83 without TLE) with 117 MR image pairs (routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR) were included.

MRI Acquisition Protocol

MRI was performed using a 3T scanner (Siemens VIDA; Siemens Healthineers, Erlangen, Germany) with a 64-channel head/neck coil. We obtained oblique coronal T2-weighted images using two different schemes: 3-mm routine MRI and 1.5-mm slice-thickness MRI. Details of the MRI acquisition protocol are provided in the Supplementary Methods.

Deep Learning-Based Reconstruction (DLR)

The acquired oblique coronal 1.5-mm slice-thickness 2D turbo spin echo T2-weighted images were reconstructed using commercially available MR image reconstruction software (SwiftMR®, v2.0.1.0. AIRS Medical, Seoul, Korea). This software employs a self-supervised learning framework to improve image quality without requiring additional scan data [22]. The algorithm includes a deep convolutional neural network component that eliminates noise from the image domain and estimates truncated high-frequency image data. This pipeline is applicable to 2D and 3D acquisitions across various anatomical regions, pulse sequences, contrast weightings, field strengths, and coil configurations. The noise reduction level was adjustable, as the model training process involved incorporating varying levels of noise on the input side. Details on the DLR are provided in the Supplementary Methods.

Image Analysis

Two readers (P.S.S. and Y.W.R., each with 2 years of experience in neuroradiology) blinded to clinical information assessed the images. Before performing the image analysis, the readers were trained using 10 sample cases that were not included in the study. A consensus was reached with an experienced neuroradiologist (J.E.P., with 10 years of experience in neuroradiology). After training, the readers independently interpreted the 351 randomly shuffled MR images over a specified 1-month period to minimize in-group bias.

Detection of Lesions and Laterality in the Temporal Lobe and Hippocampus

Initially, the readers identified whether there was an abnormality in the right or left hippocampus or right or left temporal lobe, recording the location and laterality. In the presence of bilateral lesions, laterality was considered bilateral.

Lesion Findings

Subsequently, the readers assessed lesion findings using a three-point scale. Evaluation of hippocampal lesions involved three aspects: volume loss (0 = no, 1 = moderate, 2 = severe), T2 high-signal intensity abnormality (0 = no, 1 = visible, 2 = clearly visible), and loss of the internal structure of the hippocampus (0 = no, 1 = visible, 2 = clearly visible). Higher scores indicated more severe disease. For the temporal lobe, the conspicuity of any lesion was evaluated (0 = no lesion, 1 = intermediately defined margin, and 2 = well-defined margin).

Image Quality Assessment

Example images illustrating the assessment of image quality are shown in Supplementary Figure 1. The same reader used a three-point scale to evaluate the degree of overall subjective image quality, flow and motion artifacts, sharpness, and structural conspicuity. For quantitative analysis, the SNR and CNR were calculated from routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR for 30 randomly selected patients. The ratios of SNR and CNR were calculated by dividing the SNR and CNR of 1.5-mm MRI + DLR by those of routine MRI and 1.5-mm MRI without DLR. Details of the assessment of image quality using three-point scales, SNR, and CNR are provided in the Supplementary Methods, with example images for calculating SNR and CNR shown in Supplementary Figure 2.

Reference Standards

All available MRI resources were reviewed, and the presence of abnormalities was determined by an experienced

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Korean Journal of Radiology
KJR

neuroradiologist (J.E.P.). Reference standards for the causes of epilepsy were established by two neurologists (Y.S.K. and S.L., with 20 and 35 years of experience in neurology, respectively), incorporating all available clinical histories, laboratory findings, electroencephalography (EEG) findings, surgical records, and MRI findings. Patients lacking a typical clinical presentation of seizures and exhibiting normal laboratory and EEG findings, along with negative MRI findings, were considered disease-negative. Any discrepancies in location (right hippocampus, left hippocampus, right temporal lobe, or left temporal lobe) were resolved through discussions.

Statistical Analysis

To evaluate the diagnostic performance of routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR in the diagnosis of TLE, accuracy, sensitivity, and specificity were calculated. Detection sensitivity among patients with TLE was also determined. Logistic regression with generalized estimating equations was used to compare the diagnostic performances pooled across the two readers among the MRI imaging protocols, considering the correlation between observations within each patient. McNemar's test was used to compare the performance between the protocols for each reader. Additionally, receiver operating characteristic curves were generated to evaluate diagnostic performance using lesion-finding scores, and the area under the curve (AUC) was calculated. Inter-reader agreement was calculated using Cohen's kappa statistic, with κ-values < 0.20 (poor), 0.21–0.40 (fair), 0.41–0.60 (moderate), 0.61–0.80 (substantial), and 0.81–1 (almost perfect agreement). The lesion findings and image quality scores were compared using the Friedman test. Comparisons of SNR and CNR measurements between routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR were performed using paired sample *t*-tests.

Statistical planning and analysis were performed by an experienced statistician (S.O.K., with 12 years of experience) using SAS 9.4 (SAS Institute, Cary, NC, USA) and R software (version 3.6.1; R Core Team, Vienna, Austria). A value of $P < 0.05$ was considered statistically significant. For multiple comparison, the alpha value was adjusted using Bonferroni correction ($\alpha = 0.05/3 = 0.0167$).

RESULTS

Characteristics of the Study Population

A total of 117 study patients (mean age ± standard deviation, 41 ± 16 years; 61 females) were enrolled. The clinical characteristics of the study population are summarized in Table 1. Among the 34 patients with TLE, the most common cause of TLE was hippocampal sclerosis (n = 16, 47.1%), followed by brain tumors (n = 7, 20.6%). Three patients were pathologically confirmed to have brain tumors after surgical resection (dysembryoplastic neuroepithelial tumor in two patients and polymorphous low-grade neuroepithelial tumor of the young in one patient), and four patients were diagnosed with low-grade glioma based on MRI findings and follow-up. Eight patients with TLE were diagnosed with sequelae of inflammation (n = 4, 11.8%), intracranial hemorrhage (n = 2, 5.9%), or trauma (n = 2, 5.9%).

Table 1. Clinical characteristics of the patients

Characteristic	Value
All patients	117
Patients with TLE	34 (29.1)
Age, yrs	41 ± 16
Sex, male:female	56:61
Cause of TLE	
Hippocampal sclerosis	16 (47.1)
Tumor	7 (20.6)
Post-inflammation sequelae	4 (11.8)
Post-hemorrhage sequelae	2 (5.9)
Trauma	2 (5.9)
Neuronal migration disorder	2 (5.9)
Cavernous malformation	1 (2.9)

Data are presented as mean ± standard deviation or n (%).
TLE = temporal lobe epilepsy

Diagnostic Performance for TLE

The inter-reader agreement between two readers was substantial ($\kappa = 0.647$, 95% CI: 0.545–0.749). The diagnostic performance of routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR in the diagnosis of TLE is summarized in Table 2, with detailed information listed in Supplementary Table 1. The pooled accuracy of the readers on 1.5-mm MRI + DLR (80.8%, 95% CI: 74.0–86.1) was comparable to that on routine MRI (84.2%, 95% CI: 77.7–89.1; $P = 0.371$), while the pooled sensitivity of 1.5-mm MRI + DLR (91.2%, 95% CI: 82.3–95.8) was significantly higher than that of routine MRI (72.1%, 95% CI: 56.7–83.5; $P < 0.001$). However, the pooled specificity of 1.5-mm MRI + DLR (76.5%, 95% CI: 67.7–83.5) was lower than that of routine MRI (89.2%, 95% CI: 82.6–93.4; $P = 0.004$). Figure 2 shows cases of hippocampal sclerosis on routine MRI and 1.5-mm MRI + DLR.

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Table 2. Comparison of diagnostic performance pooled across two readers between routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR

Performance parameter	Routine MRI	1.5-mm MRI without DLR	1.5-mm MRI + DLR	*P**	*P*†
Performance in the entire patients					
Accuracy	84.2 (77.7, 89.1) [197/234]	73.1 (65.5, 79.5) [171/234]	80.8 (74.0, 86.1) [189/234]	0.371	0.010
Sensitivity	72.1 (56.7, 83.5) [49/68]	83.8 (71.6, 91.4) [57/68]	91.2 (82.3, 95.8) [62/68]	< 0.001	0.064
Specificity	89.2 (82.6, 93.4) [148/166]	68.7 (59.1, 76.9) [114/166]	76.5 (67.7, 83.5) [127/166]	0.004	0.042
Sensitivity in subgroup of patients with TLE according to lesion location					
Hippocampus	75.0 (59.9, 85.8) [51/68]	86.8 (72.9, 94.1) [59/68]	92.7 (84.0, 96.8) [63/68]	0.001	0.031
Temporal lobe	89.7 (75.1, 96.2) [61/68]	82.4 (69.1, 90.7) [56/68]	92.7 (84.0, 96.8) [63/68]	0.341	0.012

Data are pooled results across the two readers in % with the 95% confidence interval in parentheses and raw numbers in brackets.
**P*-value for comparison between routine MRI and 1.5-mm MRI + DLR, †*P*-value for comparison between 1.5-mm MRI without DLR and 1.5-mm MRI + DLR. *P*-value < 0.016 indicates statistically significant difference with Bonferroni correction.
DLR = deep learning-based reconstruction, TLE = temporal lobe epilepsy

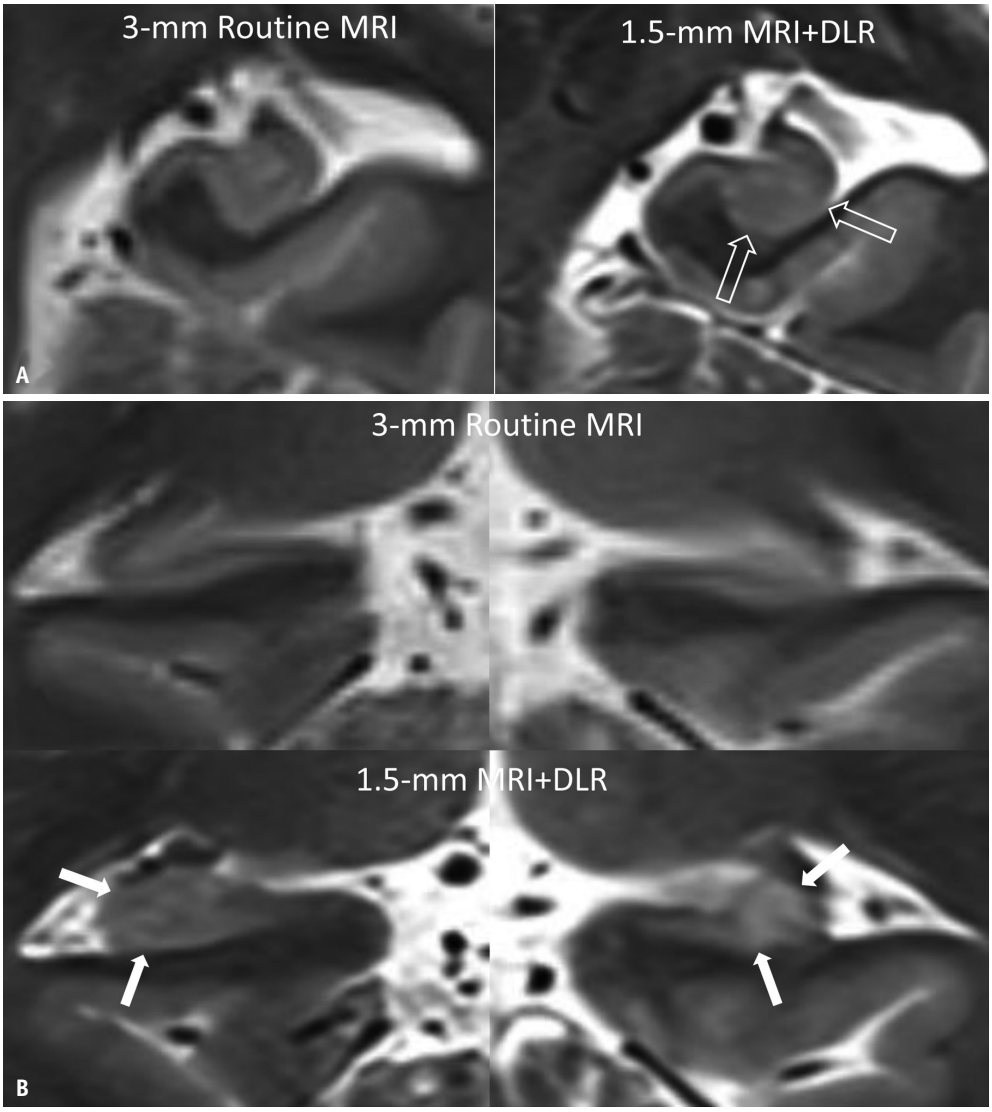

Fig. 2. Increased detection sensitivity on 1.5-mm MRI + DLR in patients with hippocampal sclerosis. **A:** Blurring of hippocampal striation in the left hippocampus is considered suspicious on routine MRI (left), but is obvious on 1.5-mm MRI + DLR (arrows, right). **B:** Routine MRI shows within-normal volume, signal intensity, and internal structure of both hippocampal tails (upper). However, 1.5-mm MRI + DLR shows increased signal intensity and blurred hippocampal striation in both hippocampal tails (arrows, lower). DLR = deep learning-based reconstruction

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Korean Journal of Radiology
KJR

In comparison with 1.5-mm MRI without DLR, the pooled accuracy was significantly improved with DLR (1.5-mm MRI without DLR: 73.1%, 95% CI: 65.5–79.5; $P = 0.010$). The pooled sensitivity and specificity of 1.5-mm MRI + DLR were higher than those of 1.5-mm MRI without DLR, although the differences were not statistically significant ($P = 0.064$ and $P = 0.042$, considering correction for multiple comparison).

False-positive (FP) results for diagnosing TLE were compared between 1.5-mm MRI + DLR and 1.5-mm MRI without DLR. Both readers 1 and 2 identified FPs in common in 12 patients on 1.5-mm MRI + DLR and 19 patients on 1.5-mm MRI without DLR. The most common FP pattern was loss of internal structure in a single slice but normal appearance in successive slices (+DLR: 58.3% vs. without DLR: 68.4%), followed by anatomic variation of the hippocampus (+DLR: 16.7% vs. without DLR: 15.8%), limited evaluation of the hippocampus because of artifact (+DLR: 16.7% vs. without DLR: 10.5%), and definite radiologic abnormality (enlarged perivascular space) but not clinically diagnosed as TLE (+DLR: 8.3% vs. without DLR: 5.3%). The patterns of false positives were similar between the images with and without DLR. The patterns of FP detection are shown in Supplementary Table 2 and examples of FP detection are shown in Figure 3.

Detection Sensitivity and Lesion Findings in the Hippocampus and Temporal Lobe in Patients with TLE

The 1.5-mm MRI + DLR showed significantly higher detection sensitivity for hippocampal lesions in patients with TLE (92.7%, 95% CI: 84.0–96.8) compared to routine MRI (75.0%, 95% CI: 59.9–85.8; $P = 0.001$) (Table 2). Additionally, 1.5-mm MRI + DLR showed higher detection sensitivity for hippocampal lesions than 1.5-mm MRI without DLR (86.8%, 95% CI: 72.9–94.1; $P = 0.031$) and for temporal lobe lesions (82.4%, 95% CI: 69.1–90.7; $P = 0.012$). The highest AUCs for diagnosing TLE according to lesion location were observed in 1.5-mm MRI + DLR, with values of 0.90 (95% CI: 0.82–0.98) for hippocampal lesions and 0.99 (95% CI: 0.97–1.00) for temporal lobe lesions (Supplementary Fig. 3).

For reader 1, abnormal hippocampal T2 high-signal intensity was significantly better depicted on 1.5-mm MRI + DLR ($P = 0.016$) than on routine MRI (Table 3). Furthermore, the loss of the internal structure of the hippocampus was significantly better delineated on 1.5-mm MRI + DLR for both readers 1 ($P < 0.001$) and 2 ($P = 0.011$). None of the lesion findings were significantly different between 1.5-mm MRI without DLR and 1.5-mm MRI + DLR.

Comparison of Image Quality: Qualitative and Quantitative Analysis

Compared with routine MRI, the 1.5-mm MRI + DLR showed significantly better structural conspicuity for both readers 1 ($P = 0.001$) and 2 ($P < 0.001$) and better sharpness for reader 2 ($P < 0.001$) (Table 3). However, flow artifacts were more frequently detected on 1.5-mm MRI + DLR than on routine MRI for both readers 1 and 2 ($P < 0.001$). Compared with 1.5-mm MRI without DLR, DLR significantly improved overall image quality, motion artifacts, sharpness, and structural conspicuity (all, $P < 0.001$).

In the quantitative analysis, the SNR of the temporal lobe on 1.5-mm MRI significantly increased by 2.31 times with the application of DLR (mean SNR ± standard deviation: 292 ± 91 using 1.5-mm MRI + DLR vs. 132 ± 34 using 1.5-mm MRI without DLR; $P < 0.001$). Similarly, DLR on 1.5-mm MRI increased CNR between the temporal lobe and brain parenchyma by 2.41 times (72 ± 41 using 1.5-mm MRI + DLR vs. 32 ± 15 using 1.5-mm MRI without DLR; $P < 0.001$). Compared with routine MRI, the SNR and CNR on 1.5-mm MRI + DLR increased 1.27 and 1.35 times, respectively, although the differences were not statistically significant. (Supplementary Table 3).

DISCUSSION

In our study, we compared the diagnostic performance of routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR in patients with and without TLE. Our findings revealed that 1.5-mm MRI + DLR showed significantly improved accuracy compared to 1.5-mm MRI without DLR, along with higher sensitivity compared to routine MRI. In the subgroup analysis, the detection sensitivity in patients with TLE, particularly for hippocampal lesions, was significantly higher on 1.5-mm MRI + DLR than on routine MRI. We attribute this improvement to the enhanced depiction of signal abnormalities and the loss of internal structures in the hippocampus. Quantitative and qualitative image analyses showed that DLR improved image quality, SNR, and CNR. Based on these findings, thin-slice MRI with DLR appears to enhance the detection of hippocampal sclerosis.

Various pathologies cause chronic focal epilepsy, including mesial-temporal sclerosis, focal cortical dysplasia, neoplasms, cerebral infarction, and post-traumatic

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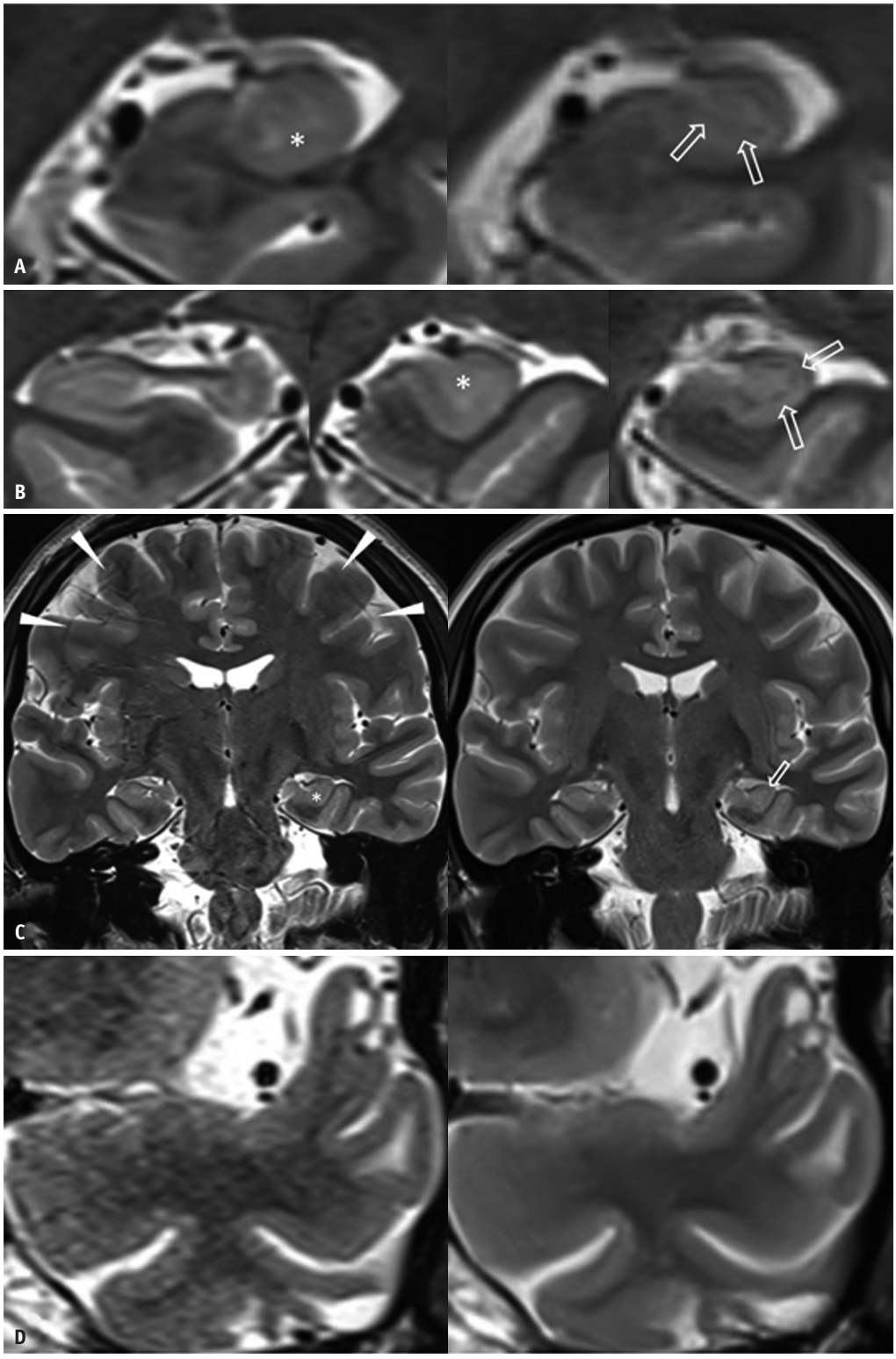

Fig. 3. Cases of false-positive detection. **A:** The internal structure within a left hippocampus of normal shape and volume is slightly blurred on 1.5-mm MRI + DLR (left, asterisk) but preserved on routine MRI (right, arrows). **B:** The internal structure of a left hippocampus with incomplete inversion is slightly blurred on 1.5-mm MRI + DLR (middle, asterisk) but preserved on routine MRI (right, arrows). The patient's EEG findings were normal. **C:** The overall image quality is fair with motion artifacts (arrowheads) on 1.5-mm MRI + DLR, and the internal structure seems blurry (asterisk, left). The internal structure is preserved on routine MRI without artifacts (arrows, right). **D:** The readers diagnosed a finding of a prominent perivascular space as encephalomalatic change on both 1.5-mm MRI + DLR and routine MRI. The EEG findings were normal in this patient. DLR = deep learning-based reconstruction, EEG = electroencephalography

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Korean Journal of Radiology
KJR

Table 3. Comparison of lesion findings and image quality between routine MRI, 1.5-mm MRI without DLR, and 1.5-mm MRI + DLR

	Reader 1					Reader 2				
	Routine MRI	1.5-mm MRI without DLR	1.5-mm MRI + DLR	*P**	*P*†	Routine MRI	1.5-mm MRI	1.5-mm MRI + DLR	*P**	*P*†
Lesion findings										
Hippocampus										
Volume loss	0.6 ± 0.8	0.5 ± 0.8	0.6 ± 0.8	1.000	0.688	0.3 ± 0.6	0.4 ± 0.7	0.4 ± 0.7	0.234	1.000
T2 high signal intensity	0.2 ± 0.5	0.4 ± 0.7	0.4 ± 0.6	0.016	1.000	0.2 ± 0.5	0.4 ± 0.6	0.3 ± 0.6	0.563	0.109
Loss of internal structure	0.2 ± 0.4	0.6 ± 0.7	0.7 ± 0.7	< 0.001	0.424	0.2 ± 0.6	0.7 ± 0.7	0.5 ± 0.7	0.011	0.070
Temporal lobe										
Lesion conspicuity	0.6 ± 0.9	0.7 ± 0.9	0.8 ± 1.0	0.250	0.563	0.6 ± 0.8	0.6 ± 0.8	0.8 ± 1.0	0.148	0.195
Image quality										
Overall image quality	2.8 ± 0.5	2.3 ± 0.7	2.8 ± 0.5	0.364	< 0.001	2.7 ± 0.6	2.2 ± 0.6	2.8 ± 0.5	0.183	< 0.001
Flow artifacts	3.0 ± 1.0	2.7 ± 0.4	2.8 ± 0.4	< 0.001	0.018	3.0 ± 0.2	2.6 ± 0.5	2.6 ± 0.5	< 0.001	0.349
Motion artifacts	2.9 ± 0.3	2.7 ± 0.6	2.9 ± 0.4	0.152	< 0.001	2.7 ± 0.6	2.6 ± 0.6	2.8 ± 0.4	0.043	< 0.001
Sharpness	2.9 ± 0.3	2.1 ± 0.6	2.9 ± 0.2	1.000	< 0.001	2.7 ± 0.5	2.1 ± 0.7	2.9 ± 0.3	< 0.001	< 0.001
Structure conspicuity	2.9 ± 0.4	2.2 ± 0.5	3.0 ± 0.1	0.001	< 0.001	2.8 ± 0.5	2.3 ± 0.5	3.0 ± 0.2	< 0.001	< 0.001

Data are presented as mean ± standard deviation.
**P*-value for comparison between routine MRI and 1.5-mm MRI + DLR, †*P*-value for comparison between 1.5-mm MRI without DLR and 1.5-mm MRI + DLR. *P*-value < 0.016 indicates statistically significant difference with Bonferroni correction.
DLR = deep learning-based reconstruction

encephalomalacia [23]. Among these, hippocampal sclerosis is the most common cause of TLE and can be identified on MRI. However, the challenge of MRI-negative TLE remains unresolved; therefore, high-resolution MRI is required. Achieving high-resolution images of the hippocampus using 3T MRI is challenging because of the trade-off between spatial resolution and image noise. Recently, the DLR technique has led to improvements in image quality and advanced anatomical imaging. Studies on various small structures, including the pituitary glands [17,18,24], prostate glands [16,19,25], and peripheral nerves [26], have demonstrated improved image quality and lesion conspicuity using the DLR technique. In our study, the impact of DLR was clearly demonstrated in the comparison between 1.5-mm MRI with and without DLR. DLR significantly improved overall image quality, motion artifacts, sharpness, and structural conspicuity in the qualitative analysis, while also increasing SNR (2.31 times) and CNR (2.41 times) in the quantitative analysis. Furthermore, when compared to routine MRI, 1.5-mm MRI + DLR showed better sharpness and structural conspicuity in qualitative analysis, along with higher SNR and CNR in quantitative analysis. This contributed to the improvement in image quality, which led to a clearer depiction of T2 high signal intensity abnormalities and loss of internal structure in the hippocampus.

As a result of these improvements, the sensitivity for the diagnosis of TLE was higher using 1.5-mm MRI + DLR than using routine MRI. Additionally, the detection sensitivity for hippocampal lesions in patients with TLE using 1.5-mm MRI + DLR was significantly higher than that using routine MRI. As epileptogenic discharges in the temporal lobe do not always indicate TLE, the accurate diagnosis of MRI-negative TLE is challenging, and invasive investigations are sometimes necessary [27,28]. We believe that 1.5-mm MRI + DLR is beneficial for determining and localizing the epileptogenic focus, planning surgical management, and reducing the need for invasive investigations such as stereotaxic depth electrode implantation. Our results indicate that thin-slice MRI with DLR enhances the detection performance for hippocampal abnormalities, thus decreasing the proportion of patients with MRI-negative TLE and increasing the proportion of patients eligible for curative surgery.

Notably, the specificity of 1.5-mm MRI + DLR was lower than that of routine MRI. We retrospectively reviewed 27 FP lesions (for both readers) and found that most (77.8%) showed loss of internal structure in a single slice but were normal in successive slices, which diminished the specificity for TLE. Since additional findings, including atrophy, T2 signal intensity abnormalities, and loss of digitations of the hippocampal head, are frequently detected in hippocampal sclerosis [29,30], a single finding of loss of internal structure in a single slice should be cautiously interpreted.

Our study had several limitations. First, we included

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both disease-positive and disease-negative patients in this retrospective study to assess diagnostic performance, resembling conditions in actual clinical settings. However, a prospective study including other types of focal epilepsy is required. Second, the readers were blinded to all patient information, including slice thickness; however, an inherent bias may still have been present in the image evaluation. Third, MRI is routinely performed with a 3-mm slice thickness in clinical practice, as in our institution, despite partial volume averaging effects [31] that result in poor delineation of small structures. As the HARNESS-MRI protocol recommends images with a 2-mm slice thickness for evaluating the hippocampus, this also needs to be evaluated in the future. Finally, only 8.8% of the patients underwent surgery with pathological confirmation. We attempted to overcome this issue by constructing a reference standard based on the clinicoradiological consensus of experienced neurologists and neuroradiologists. A multicenter validation with surgical confirmation in a larger population is necessary.

In conclusion, 1.5-mm MRI + DLR showed higher diagnostic performance for TLE compared to routine MRI and 1.5-mm MRI without DLR, which is attributed to improved image quality, SNR, and CNR. Specifically, 1.5-mm MRI + DLR showed benefits in evaluating the internal structure and signal abnormalities of the hippocampus, resulting in increased detection sensitivity for identifying hippocampal abnormalities. These findings underscore the significance of thin-slice imaging with DLR and its potential to reduce the number of MRI-negative TLE cases.

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2023.0842.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Ji Eun Park. Data curation: Pae Sun Suh, Ji Eun Park. Formal analysis: Pae Sun Suh, Ji Eun Park, Seonok Kim. Funding acquisition: Ji Eun Park. Investigation: Pae Sun Suh, Ji Eun Park, Yun Hwa Roh. Methodology: Ji Eun Park. Project administration: Ji Eun Park, Yangsean Choi, Ho Sung Kim. Supervision: Ji Eun Park. Visualization: Pae Sun Suh, Ji Eun Park. Writing—original draft: Pae Sun Suh. Writing—review&editing: all authors.

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REFERENCES

1. Engel J Jr, McDermott MP, Wiebe S, Langfitt JT, Stern JM, Dewar S, et al. Early surgical therapy for drug-resistant temporal lobe epilepsy: a randomized trial. *JAMA* 2012;307:922-930
2. Jones AL, Cascino GD. Evidence on use of neuroimaging for surgical treatment of temporal lobe epilepsy: a systematic review. *JAMA Neurol* 2016;73:464-470
3. Cascino GD, Jack CR Jr, Parisi JE, Sharbrough FW, Hirschorn KA, Meyer FB, et al. Magnetic resonance imaging-based volume studies in temporal lobe epilepsy: pathological correlations.

Ann Neurol 1991;30:31-36
4. Bien CG, Szinay M, Wagner J, Clusmann H, Becker AJ, Urbach H. Characteristics and surgical outcomes of patients with refractory magnetic resonance imaging-negative epilepsies. *Arch Neurol* 2009;66:1491-1499
5. Winston GP, Micallef C, Kendell BE, Bartlett PA, Williams EJ, Burdett JL, et al. The value of repeat neuroimaging for epilepsy at a tertiary referral centre: 16 years of experience. *Epilepsy Res* 2013;105:349-355
6. Muhlhofer W, Tan YL, Mueller SG, Knowlton R. MRI-negative temporal lobe epilepsy—what do we know? *Epilepsia* 2017;58:727-742
7. Vargas MI, Martelli P, Xin L, Ipek O, Grouiller F, Pittau F, et al. Clinical neuroimaging using 7 T MRI: challenges and prospects. *J Neuroimaging* 2018;28:5-13
8. Barisano G, Sepehrband F, Ma S, Jann K, Cabeen R, Wang DJ, et al. Clinical 7 T MRI: are we there yet? A review about magnetic resonance imaging at ultra-high field. *Br J Radiol* 2019;92:20180492
9. Santyr BG, Goubran M, Lau JC, Kwan BYM, Salehi F, Lee DH, et al. Investigation of hippocampal substructures in focal temporal lobe epilepsy with and without hippocampal sclerosis at 7T. *J Magn Reson Imaging* 2017;45:1359-1370
10. Stefanits H, Springer E, Pataraia E, Baumgartner C, Hainfellner JA, Prayer D, et al. Seven-tesla MRI of hippocampal sclerosis: an in vivo feasibility study with histological correlations. *Invest Radiol* 2017;52:666-671
11. Henry TR, Chupin M, Lehéricy S, Strupp JP, Sikora MA, Sha ZY, et al. Hippocampal sclerosis in temporal lobe epilepsy: findings at 7 T. *Radiology* 2011;261:199-209
12. Zhang Y, Lv Y, You H, Dou W, Hou B, Shi L, et al. Study of the hippocampal internal architecture in temporal lobe epilepsy using 7 T and 3 T MRI. *Seizure* 2019;71:116-123
13. Bernasconi A, Cendes F, Theodore WH, Gill RS, Koepp MJ, Hogan RE, et al. Recommendations for the use of structural magnetic resonance imaging in the care of patients with epilepsy: a consensus report from the international league against epilepsy neuroimaging task force. *Epilepsia* 2019;60:1054-1068
14. Sijbers J, Scheunders P, Bonnet N, Van Dyck D, Raman E. Quantification and improvement of the signal-to-noise ratio in a magnetic resonance image acquisition procedure. *Magn Reson Imaging* 1996;14:1157-1163
15. Lebel RM. Performance characterization of a novel deep learning-based MR image reconstruction pipeline. arXiv [Preprint]. 2020 [accessed on March 21, 2023]. Available at: https://doi.org/10.48550/arXiv.2008.06559
16. Park JC, Park KJ, Park MY, Kim MH, Kim JK. Fast T2-weighted imaging with deep learning-based reconstruction: evaluation of image quality and diagnostic performance in patients undergoing radical prostatectomy. *J Magn Reson Imaging* 2022;55:1735-1744
17. Kim M, Kim HS, Kim HJ, Park JE, Park SY, Kim YH, et al. Thin-slice pituitary MRI with deep learning-based reconstruction: diagnostic performance in a postoperative setting. *Radiology* 2021;298:114-122
18. Lee DH, Park JE, Nam YK, Lee J, Kim S, Kim YH, et al. Deep learning-based thin-section MRI reconstruction improves tumour detection and delineation in pre- and post-treatment pituitary adenoma. *Sci Rep* 2021;11:21302
19. Ueda T, Ohno Y, Yamamoto K, Murayama K, Ikedo M, Yui M, et al. Deep learning reconstruction of diffusion-weighted MRI improves image quality for prostatic imaging. *Radiology* 2022;303:373-381
20. Yasaka K, Akai H, Sugawara H, Tajima T, Akahane M, Yoshioka N, et al. Impact of deep learning reconstruction on intracranial 1.5 T magnetic resonance angiography. *Jpn J Radiol* 2022;40:476-483
21. Iwamura M, Ide S, Sato K, Kakuta A, Tatsuo S, Nozaki A, et al. Thin-slice two-dimensional T2-weighted imaging with deep learning-based reconstruction: improved lesion detection in the brain of patients with multiple sclerosis. *Magn Reson Med Sci* 2023 Mar 16. [Epub]. https://doi.org/10.2463/mrms.mp.2022-0112
22. Jung W, Lee HS, Seo M, Nam Y, Choi Y, Shin NY, et al. MR-self Noise2Noise: self-supervised deep learning-based image quality improvement of submillimeter resolution 3D MR images. *Eur Radiol* 2023;33:2686-2698
23. Abud LG, Thivard L, Abud TG, Nakiri GS, Santos AC, Dormont D. Partial epilepsy: a pictorial review of 3 TESLA magnetic resonance imaging features. *Clinics (Sao Paulo)* 2015;70:654-661
24. Kim M, Kim HS, Park JE, Park SY, Kim YH, Kim SJ, 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
25. Wang X, Ma J, Bhosale P, Ibarra Rovira JJ, Qayyum A, Sun J, et al. Novel deep learning-based noise reduction technique for prostate magnetic resonance imaging. *Abdom Radiol (NY)* 2021;46:3378-3386
26. Zochowski KC, Tan ET, Argentieri EC, Lin B, Burge AJ, Queler SC, et al. Improvement of peripheral nerve visualization using a deep learning-based MR reconstruction algorithm. *Magn Reson Imaging* 2022;85:186-192
27. Kim SE, Andermann F, Olivier A. The clinical and electrophysiological characteristics of temporal lobe epilepsy with normal MRI. *J Clin Neurol* 2006;2:42-50
28. Andermann F. Pseudotemporal vs neocortical temporal epilepsy: things aren't always where they seem to be. *Neurology* 2003;61:732-733
29. Bronen RA, Fulbright RK, Kim JH, Spencer SS, Spencer DD, al-Rodhan NR. Regional distribution of MR findings in hippocampal sclerosis. *AJNR Am J Neuroradiol* 1995;16:1193-1200
30. Oppenheim C, Dormont D, Biondi A, Lehéricy S, Hasboun D, Clémenceau S, et al. Loss of digitations of the hippocampal head on high-resolution fast spin-echo MR: a sign of mesial temporal sclerosis. *AJNR Am J Neuroradiol* 1998;19:457-463
31. Erasmus L, Hurter D, Naudé M, Kritzinger H, Acho S. A short overview of MRI artefacts. *SA J Radiol* 2004;8:13-17