European Radiology (2019) 29:2641–2650
https://doi.org/10.1007/s00330-018-5812-5

NEURO

Reliability of fast magnetic resonance imaging for acute ischemic stroke patients using a 1.5-T scanner

Mi Sun Chung[1] · Ji Ye Lee[2] · Seung Chai Jung[3] · Seunghee Baek[4] · Woo Hyun Shim[3] · Ji Eun Park[3] · Ho Sung Kim[3] · Choong Gon Choi[3] · Sang Joon Kim[3] · Deok Hee Lee[3] · Sang-Beom Jeon[5] · Dong-Wha Kang[5] · Sun U. Kwon[5] · Jong S. Kim[5]

Received: 15 May 2018 / Revised: 13 September 2018 / Accepted: 28 September 2018 / Published online: 12 November 2018

Abstract

Objectives To determine whether fast scanned MRI using a 1.5-T scanner is a reliable method for the detection and characterization of acute ischemic stroke in comparison with conventional MRI.

Methods From May 2015 to June 2016, 862 patients (FLAIR, $n = 482$; GRE, $n = 380$; MRA, $n = 190$) were prospectively enrolled in the study, with informed consent and under institutional review board approval. The patients underwent both fast (EPI-FLAIR, ETL-FLAIR, TR-FLAIR, EPI-GRE, parallel-GRE, fast CE-MRA) and conventional MRI (FLAIR, GRE, time-of-flight MRA, fast CE-MRA). Two neuroradiologists independently assessed agreements in acute and chronic ischemic hyperintensity, hyperintense vessels (FLAIR), microbleeds, susceptibility vessel signs, hemorrhagic transformation (GRE), stenosis (MRA), and image quality (all MRI), between fast and conventional MRI. Agreements between fast and conventional MRI were evaluated by generalized estimating equations. Z-scores were used for comparisons of the percentage agreement among fast FLAIR sequences and fast GRE sequences and between conventional and fast MRA.

Results Agreements of more than 80% were achieved between fast and conventional MRI (ETL-FLAIR, 96%; TR-FLAIR, 97%; EPI-GRE, 96%; parallel-GRE, 98%; fast CE-MRA, 86%). ETL- and TR-FLAIR were significantly superior to EPI-FLAIR in the detection of acute ischemic hyperintensity and hyperintense vessels, while parallel-GRE was significantly superior to EPI-GRE in the detection of susceptibility vessel sign (p value < 0.05 for all). There were no significant differences in the other scores and image qualities (p value > 0.05).

Conclusions Fast MRI at 1.5 T is a reliable method for the detection and characterization of acute ischemic stroke in comparison with conventional MRI.

Key Points

- *Fast MRI at 1.5 T may achieve a high intermethod reliability in the detection and characterization of acute ischemic stroke with a reduction in scan time in comparison with conventional MRI.*

Keywords Stroke · Magnetic resonance imaging · Magnetic resonance angiography

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00330-018-5812-5) contains supplementary material, which is available to authorized users.

✉ Seung Chai Jung
dynamics79@gmail.com

[1] Department of Radiology, Chung-Ang University Hospital, Seoul, South Korea

[2] Department of Radiology, Soonchunhyang University Bucheon Hospital, Wonmi-gu, Bucheon, South Korea

[3] Department of Radiology and Research Institute of Radiology, Asan Medical Center, University of Ulsan College of Medicine, 88 Olympic-ro 43-gil, Song pa-gu, Seoul 138-736, South Korea

[4] Department of Clinical Epidemiology and Biostatistics, Asan Medical Center, University of Ulsan College of Medicine, Seoul, South Korea

[5] Department of Neurology, Asan Medical Center, University of Ulsan College of Medicine, Seoul, South Korea

Abbreviations

CT	Computed tomography
DWI	Diffusion-weighted imaging
EPI	Echo-planar imaging
EPI-FLAIR	FLAIR using echo-planar imaging
EPI-GRE	GRE using echo-planar imaging
ETL-FLAIR	FLAIR with increased echo train length
Fast CE-MRA	Contrast-enhanced MRA with increased acceleration factor and slice thickness
FLAIR	Fluid-attenuated inversion recovery
GRE	Gradient echo T2*-weighted imaging
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
Parallel-GRE	GRE with increased acceleration factor
PWI	Perfusion-weighted imaging

Introduction

Multimodal magnetic resonance imaging (MRI) is useful for the diagnosis of ischemic stroke, allowing determination of appropriate treatment strategies in the acute phase and facilitating the prediction of outcome for stroke patients [1]. MRI for acute ischemic stroke generally consists of diffusion-weighted imaging (DWI), dynamic susceptibility contrast perfusion-weighted imaging (PWI), fluid-attenuated inversion recovery (FLAIR), gradient echo T2*-weighted imaging (GRE), and magnetic resonance angiography (MRA) [1, 2]. MRI provides higher sensitivity for the detection of acute ischemia and acute and chronic hemorrhage than computed tomography (CT), without the ionizing radiation [1, 3, 4]. However, the longer scan times and lower availability of MRI in comparison with CT are critical obstacles to the MRI of acute ischemic stroke [2]. In previous randomized controlled studies, the scan time for multimodal MRI for acute ischemic stroke has generally been more than 20 min [5–7]. Furthermore, as early recanalization through mechanical thrombectomy is vital for improving patients' outcomes, CT has become the main modality for the detection and characterization of acute ischemic stroke [8].

Nael et al suggested a 6-min MRI protocol for acute ischemic stroke, which was based on echo-planar imaging (EPI) on a 3-T scanner [2]. However, the 6-min MRI protocol has drawbacks, in that 3-T scanners have lower availability than 1.5-T scanners, and the EPI images acquired had a poor image quality for depiction of acute ischemic stroke. We hypothesized that, in comparison with conventional MRI using non-fast scanning sequences, fast scanned sequences (fast MRI) on a 1.5-T scanner could decrease scan time while preserving diagnostic performance for acute ischemic stroke. We therefore evaluated the following fast MRI sequences: FLAIR using EPI (EPI-FLAIR) [2, 9–11], FLAIR with increased echo train length (ETL-FLAIR) [12], FLAIR with decreased repetition time (TR-FLAIR) [13], GRE using EPI (EPI-GRE) [2], GRE with increased acceleration factor (parallel-GRE), and contrast- enhanced MRA with increased acceleration factor and slice thickness (fast CE-MRA) [14].

We therefore aimed to determine whether fast MRI on a 1.5-T scanner is a reliable method for the detection and characterization of acute ischemic stroke in comparison with conventional MRI.

Materials and methods

Study population

Between May 2015 and June 2016, 862 patients undergoing MRI (FLAIR [$n = 482$], GRE [$n = 380$], and MRA [$n = 190$]) at a single tertiary hospital for symptoms of acute ischemic stroke were prospectively and consecutively enrolled. The inclusion criteria were as follows: (*a*) patients who visited the emergency room of our institution because of symptoms of acute ischemic stroke, (*b*) patients who underwent brain MRI and MRA using fast and conventional MRI, (*c*) patients without any contraindications to MR imaging and contrast material usage. Each fast MRI sequence was arbitrarily added to the conventional MRI (EPI-FLAIR [$n = 228$], ETL-FLAIR [$n = 228$], TR-FLAIR [$n = 228$], EPI-GRE and parallel-GRE [$n = 380$], and fast CE-MRA [$n = 190$]). The total number of patients undergoing a fast FLAIR sequence was 482, as one or two fast FLAIR sequences were added to the protocol for a single patient (Fig. 1). In our institute, intravenous thrombolysis is determined on non-contrast CT, which is used as the first imaging modality, and further treatment is determined according to fast MRI sequences obtained on a MR scanner dedicated to acute ischemic stroke. The demographic and clinical data of patients were collected, including age, sex, body mass index, hypertension, diabetes mellitus, hyperlipidemia, obesity, alcohol and smoking history, activity and family history of stroke, and past medical history such as heart disease, history of stroke, and National Institutes of Health Stroke Scale rating (NIHSS) (Supplemental Tables 1 and 2). This prospective study was approved by our institutional review board, and written informed consent was obtained from all enrolled patients. This study is reported in accordance with Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [15].

Imaging acquisition

All MRI was performed on a 1.5-T scanner (Magnetom Avanto; Siemens Healthineers). The conventional MRI consisted of DWI (scan time, 81 s), PWI (scan time, 61 s), GRE (scan time, 141 s), FLAIR (scan time, 128 s), time-of-flight MRA for intracranial vessels (TOF-MRA; scan time,

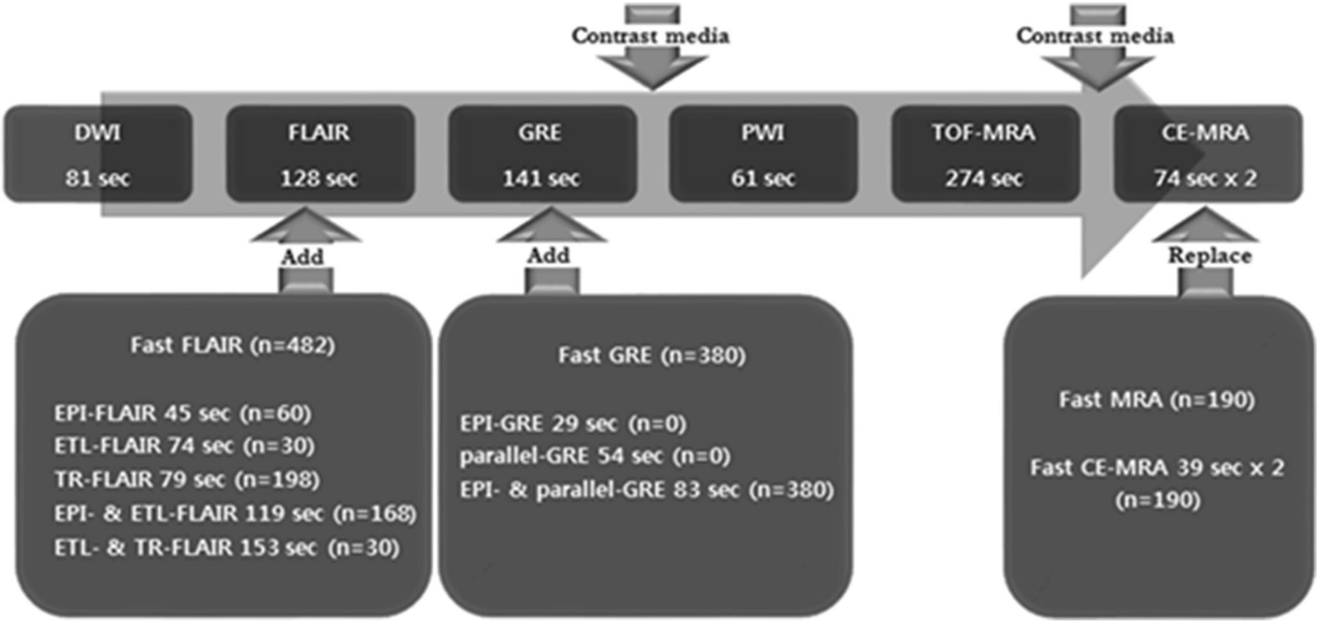

Fig. 1 Flowchart of conventional and fast MRI

274 s), and contrast-enhanced head and neck MRA (CE-MRA; scan time, 74 s). The fast MRI sequences used were as follows: EPI-FLAIR (scan time, 45 s), ETL-FLAIR (scan time, 74 s), TR-FLAIR (scan time, 79 s), EPI-GRE (scan time, 29 s), parallel-GRE (scan time, 54 s), and fast CE-MRA (scan time, 39 s) for TOF-MRA for intracranial vessels and contrast-enhanced head and neck MRA.

The fast CE-MRA acquisitions were obtained after intravenous administration of gadoterate meglumine (Dotarem; Guerbet) at a dose of 0.1 mmol kg^{-1} of body weight and covered the aortic arch to the intracranial arteries. Three dimensional TOF- and CE-MRA were reconstructed using a maximum intensity projection algorithm. For the fast CE-MRA, the intracranial arteries and whole intracranial and extracranial arteries were reconstructed separately. The detailed scan parameters for the conventional and fast MRI sequences are listed in Table 1.

Image analysis

The primary study outcomes were agreements between fast and conventional MRI in the detection for acute ischemic hyperintensity on FLAIR, microbleeds on GRE, and steno-occlusion on MRA. Two experienced neuroradiologists (MSC and JSC; with 5 years and 8 years of experience, respectively) independently reviewed all of the MR imaging, while being blind to the clinical data.

Acute and chronic ischemic hyperintensities and hyperintense vessels were evaluated on both conventional and fast FLAIR sequences. Acute ischemic hyperintensity was defined as high signal intensity on FLAIR in the area corresponding to high signal intensity on DWI [16, 17]. Chronic ischemic hyperintensity was defined as hyperintensity outside of the high signal intensity on DWI. A hyperintense vessel was defined as a linear or serpentine hyperintensity on FLAIR corresponding to a typical arterial course [18]. The FLAIR sequences for acute and chronic ischemic hyperintensity were assessed according to a visual scoring system, which classified the degree of agreement between fast and conventional FLAIR sequences as follows: 1, completely discordant; 2, $< 50\%$ of area showing concordance; 3, $\geq 50\%$ and $< 90\%$ of area showing concordance; and 4, $\geq 90\%$ of area showing concordance. Hyperintense vessels on FLAIR sequences were assessed according to a visual scoring system that classified the degree of agreement between fast and conventional FLAIR sequences as follows: 1, completely discordant; 2, partially concordant; 3, completely concordant. Agreement between fast and conventional FLAIR was defined as more than a 50% area of concordance for the primary outcome.

In addition, two neuroradiologists (MSC and JYL; with 5 and 4 years of experience, respectively) used an in-house program (based on ImageJ software; National Institutes of Health, Bethesda, MD) to perform quantitative analyses for early and chronic ischemic hyperintensity. Overlapping ratios between the fast and conventional FLAIR sequences were evaluated using the Dice index ($2 \times$ the area of the intersection between the conventional and fast FLAIR / [area of conventional FLAIR] + [area of fast FLAIR]; Supplemental Fig. 1). The signal intensity of fast FLAIR sequences relative to conventional FLAIR sequences was recorded as one of three grades (lower, similar, and higher). Signal intensity ratio, apparent signal-to-noise ratio, and contrast-to noise ratio for acute ischemic hyperintensity were also calculated (Supplemental Fig. 1).

Table 1 Scan parameters

	FLAIR				GRE			MRA	
	Conventional	EPI	ETL	TR	Conventional	EPI	Parallel	Conventional CE-MRA	Fast CE-MRA
TR/TE	9000/109	9000/101	9000/102	5560/109	690/16	2260/48	765/26	3.67/1.31	3.37/1.2
Inversion time	2500	2000	2500	1930					
Flip angle	150†	180†	150†	150†	15	90	20	30	25
Matrix	256 × 218	128 × 128	192 × 192	256 × 256	256 × 205	192 × 192	192 × 163	320 × 320	448 × 367
Field of view	210 × 184	230 × 230	210 × 184	210 × 184	210 × 210	230 × 230	220 × 220	320 × 240	340 × 276
Slice thickness (mm)	5	5	5	5	5	5	5	0.5	0.8
ETL	21	128 (EPI)	32	21		192 (EPI)			
GRAPPA	2	2	2	2		2	3	2	3
NAV	1	2	1	1	1	10	1	1	1
Scan time (s)	128	45	74	79	141	29	54	74	39

CE-MRA contrast-enhanced MR angiography, *EPI* echo-planar imaging, *ETL* echo train length, *TR* repetition time, *TE* echo time, *GRAPPA* generalized autocalibrating partial parallel acquisition, *NAV* number of signal averaging

† Refocusing flip angle of conventional and fast FLAIR sequences

Table 2 Agreement between conventional and fast FLAIR

		EPI-FLAIR	ETL-FLAIR	TR-FLAIR	*p* value
Acute ischemic hyperintensity					0.45 (EPI-FLAIR), < 0.001 (ETL-FLIAR and TR-FLAIR)†
	Concordance ≥ 50%	82.0% (180/219) 0.769–0.871	95.8% (219/228) 0.932–0.985	96.7% (255/264) 0.945–0.989	< 0.001††
	Dice index	0.65 (0.26–0.95)	0.69 (0.20–0.94)	0.72 (0.38–0.97)	< 0.001††
	Relative signal intensity (lower:similar:higher)	4:139:65	1:173:53	7:172:78	< 0.001††
Hyperintense vessels					
	Concordance ≥ partial	7.1% (4/56) 0.003–0.138	87.0% (54/62) 0.768–0.972	92.9% (65/70) 0.869–0.990	< 0.001††
Chronic ischemic hyperintensity					
	Concordance ≥ 50%	99.0% (310/313) 0.98–1.00	99.7% (310/311) 0.991–1.00	100% (314/314) NE	> 0.05††
	Dice index	0.67 (0.31–0.99)	0.74 (0.40–0.92)	0.77 (0.50–0.98)	> 0.05††
	Relative signal intensity (lower:similar:higher)	28:258:26	41:236:3	19:294:0	> 0.05††
Image quality	3.0 ± 0.3 (2–4)†††	3.1 ± 0.4 (2–4)	3.1 ± 0.5 (2–4)	2.9 ± 0.5 (2–4)	> 0.05††

EPI echo-planar imaging, *ETL* echo train length, *TR* repetition time

† Comparison between expected agreement (80%) and percent of concordance ≥ 50% for early ischemic hyperintensity

†† Comparison among three fast FLAIR sequences

††† Image quality of conventional FLAIR

For GRE, microbleeds, susceptibility vessel sign, and hemorrhagic transformation were assessed according to the presence or absence of each finding. Microbleeds were regarded as small (< 5 mm of diameter) hypointense lesions with blooming artifact [19]. Susceptibility vessel sign was defined as a hypointense lesion with blooming artifact in a vessel [1], and hemorrhagic transformation as an abnormally hypointense area corresponding to the area of acute ischemic stroke, including petechial hemorrhage or parenchymatous hemorrhage [20]. The conspicuities of microbleeds, susceptibility vessel sign, and hemorrhagic transformation on fast GRE were assessed according to three grades (lower, similar, and higher) with respect to conventional GRE.

For MRA, the presence of steno-occlusion (presence or absence of steno-occlusion; < 50% vs ≥ 50% stenosis; absence of steno-occlusion vs < 50% stenosis vs ≥ 50% stenosis) in 12 segments of the intracranial arteries (two internal carotid arteries, two middle cerebral arteries, two anterior cerebral arteries, two posterior cerebral arteries, two vertebral arteries, basilar artery, and posterior inferior cerebellar artery) was evaluated on TOF-MRA and fast CE-MRA. The image quality was classified according to four grades (poor, not interpretable; moderate, some distortion and noise limiting the detailed delineation of major structures; good, minimal distortion with detailed delineation of all structures; excellent, no distortion). For MRA, the image quality was assessed between fast CE-MRA and two conventional CE-MRA acquisitions: conventional CE-MRA acquired from different patients on the same MRI scanner was used for some comparisons ($n = 190$), while conventional CE-MRA acquired from the same patients on different MRI scanners ($n = 54$) was used for the other comparisons [2].

Statistical analysis

The sample sizes were estimated by considering the percentage of agreement between conventional and fast MRI. We considered an expected agreement of 90% between conventional and fast MRI and aimed to achieve an agreement of more than 80%. Prior to patient enrollment, 50 patients who underwent a MR scan were reviewed, and the prevalence of positive findings for the primary outcome of fast MRI (50%

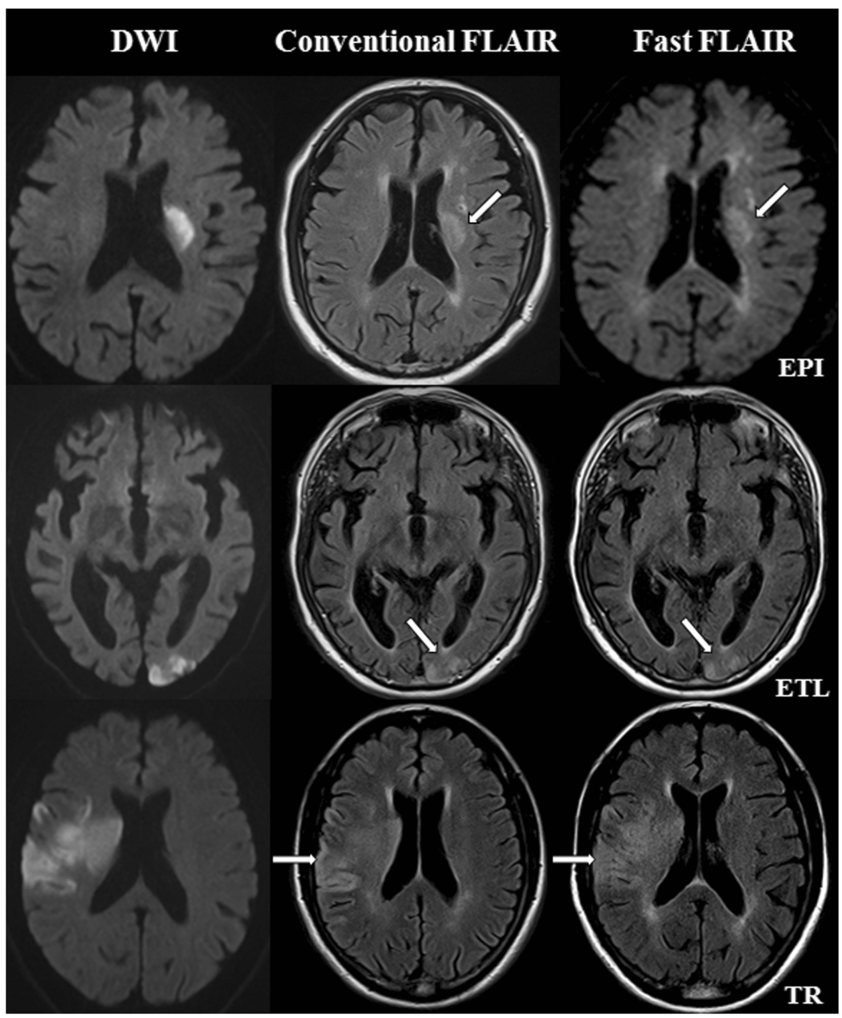

Fig. 2 Acute ischemic hyperintensity on fast and conventional FLAIR. Acute ischemic hyperintensity (arrows) in a diffusion-restricted area is well demonstrated in both fast FLAIR (EPI-FLAIR [top, scan time 45 s], ETL-FLAIR [middle, scan time 74 s], and TR-FLAIR [bottom, scan time 79 s]) and conventional FLAIR (scan time 128 s)

for FLAIR, 30% for GRE, and 60% for MRA) was evaluated. The assumed dropout rate for the estimated sample size was 20%. Sample sizes of 228 for FLAIR, 380 for GRE, and 190 for MRA were calculated, with consideration of the prevalence of positive findings and dropout rate. For the direct comparison of fast and conventional MRI, the comparison of sequences from a single individual is mandatory. However, with consideration of the ethical issues concerning the lengthening of scan time in acute stroke patients, we performed various combinations of fast and conventional MRI and finally enrolled 862 patients (482 for FLAIR, 380 for GRE, and 190 for MRA). One-sided p values less than 0.05 were considered to indicate statistical significance.

The summary statistics are presented as the number and percentages for categorical variables and the means with standard deviation for continuous variables. Agreement of fast and conventional MRI was compared using a generalized estimating equation with logit link and a compound symmetry structure to account for clustering effects within the same subject or the same observer. All agreements between fast MRI and conventional MRI were calculated by pooling the analysis of the two observers. Z-scores were used for comparisons of the percentage agreement among fast FLAIR sequences (EPI-FLAIR, ETL-FLAIR, and TR-FLAIR) and among fast GRE sequences (EPI-GRE and parallel-GRE). Z-scores were also used to test the statistical significance of agreement of MRA. We also evaluated agreements and the overlapping index according to the time interval from symptom onset to MRI on EPI-FLAIR, ETL-FLAIR, and TR-FLAIR (< 3 h, 3–6 h, 6–24 h, and more than 24 h), and subgroup analysis was performed for number of microbleeds classified by location. Intraclass correlation coefficients and weighted kappa values were used for the calculation of interobserver agreement in MRI findings. The strength of agreement of the intraclass correlation coefficients and k-values was categorized as follows: less than 0.20, poor; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, good; and 0.81–1.00, excellent. All statistical analyses were performed using the statistical software packages MedCalc for Windows (version 15.0; MedCalc Software, Ostend, Belgium) and SPSS (version 20.0; SPSS, Chicago, IL). Two-sided p values less than 0.05 were considered to indicate statistical significance.

Results

FLAIR sequences

For acute ischemic hyperintensity, ETL- and TR-FLAIR demonstrated an agreement with conventional FLAIR of more than 80% in the pooled analysis (Table 2). EPI-FLAIR demonstrated a significantly lower agreement than ETL- and TR-FLAIR (all p values < 0.001). No significant difference was found between ETL- and TR-FLAIR (p value > 0.05) (Fig. 2). In the quantitative analysis of the fast FLAIR sequences, TR-FLAIR showed the highest value for the Dice index of acute and chronic ischemic hyperintensity. Evaluation of relative signal intensity showed poorer visualization of acute ischemic hyperintensity by EPI-FLIAR than by ETL-FLIAR and TR-FLAIR (p value < 0.001). However, signal intensity ratio, apparent signal-to-noise ratio, and contrast-to-noise ratio were all lower for fast FLAIR than for conventional FLAIR, except for the signal intensity ratio and apparent signal-to-noise ratio of EPI-FLAIR and signal intensity ratio of ETL-FLAIR (Supplemental Table 3). There was no significant difference in agreement and overlapping index for any of the fast FLAIR

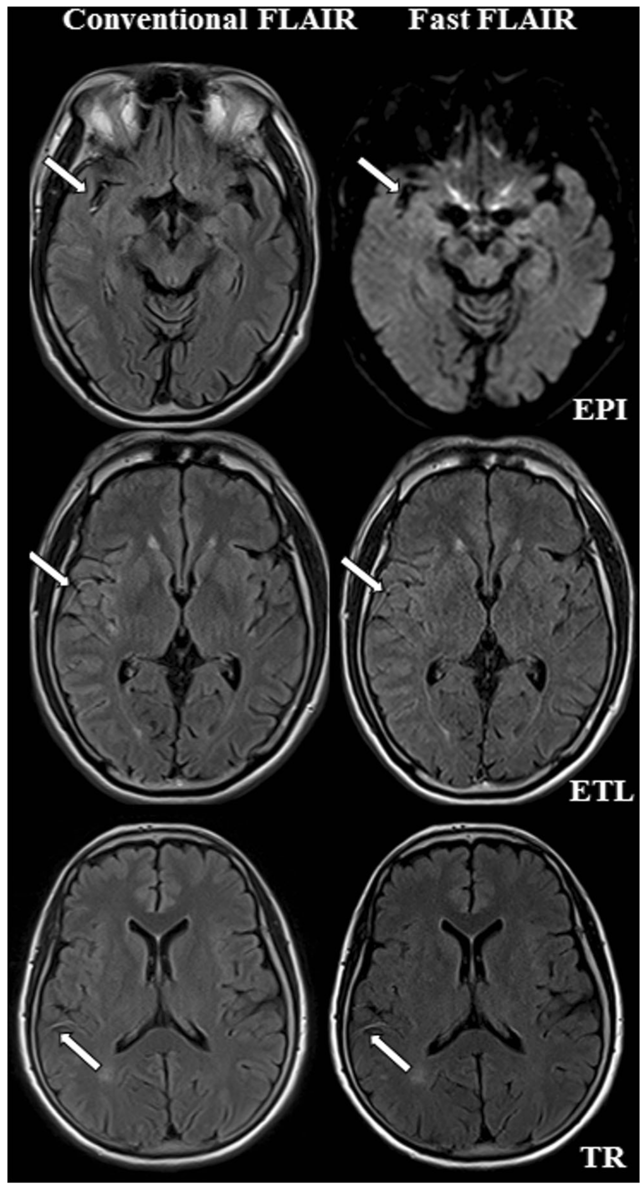

Fig. 3 Hyperintense vessels on fast and conventional FLAIR. ETL-FLAIR (middle) and TR-FLAIR (bottom) show a high agreement for hyperintense vessels (arrows) in comparison with conventional FLAIR, whereas EPI-FLAIR (top) does not

Table 3 Agreement between fast and conventional GRE

		EPI-GRE	Parallel-GRE	p value
Agreement				$< 0.001^{\dagger}$
	Microbleed	95.8% (0.923–0.977)	98.3% (0.955–0.993)	$0.101^{\dagger\dagger}$
	Susceptibility vessel sign	65.3% (0.511–0.772)	98.0% (0.869–0.997)	$0.001^{\dagger\dagger}$
	Hemorrhagic transformation	100% (0.885–1.000)	100% (0.885–1.000)	$NE^{\dagger\dagger}$
Conspicuity (lower:similar:higher)		84:207:8	6:180:108	$< 0.001^{\dagger\dagger}$
Image quality	3.7 ± 0.4 (2–4)†††	3.5 ± 0.5 (2–4)	3.5 ± 0.5 (2–4)	$> 0.05^{\dagger\dagger}$

Parentheses indicate one-sided 95% confidence intervals for agreement and range of scores for image quality

EPI echo-planar imaging

† Comparison between expected agreement (80%) and agreement (conventional and fast GRE) for microbleeds

†† Comparison between EPI-GRE and parallel-GRE

††† Image quality of conventional GRE

sequences according to the time interval from symptom onset to MRI (p value > 0.05). For hyperintense vessels, ETL- and TR-FLAIR showed an agreement with conventional FLAIR of more than 80%, and EPI-FLAIR demonstrated significantly lower agreement than ETL- and TR-FLAIR (all p values < 0.001) (Fig. 3). For chronic ischemic hyperintensity, fast FLAIR demonstrated an agreement with conventional FLAIR of more than 98% (Table 2). The fast FLAIR sequences did not differ significantly in relative signal intensity for the detection of chronic ischemic hyperintensity (p value > 0.5 for all). Image qualities were similar for conventional FLAIR and fast FLAIR sequences (p value > 0.5 for all). Interobserver agreements between the two observers were greater than or equal to moderate agreement (Supplemental Table 4).

GRE

For microbleeds, fast GRE demonstrated an agreement with conventional GRE of more than 90%, and no significant difference was found between EPI- and parallel-GRE (p value > 0.05) (Table 3 and Fig. 4). However, EPI-GRE demonstrated a significantly lower agreement than parallel-GRE for the detection of susceptibility vessel sign (65.3% vs 98.0%, p value < 0.001). Hemorrhagic transformation demonstrated a 100% agreement on both of the fast GRE sequences, and there was no significant difference between EPI- and parallel-GRE (p value > 0.05). In evaluating conspicuity, EPI-GRE was inferior to parallel-GRE (p value < 0.001). Image qualities were similar for conventional GRE, EPI-GRE, and parallel-GRE (p value > 0.5 for all). Interobserver agreements between the two observers were moderate (Supplemental Table 4). Subgroup analysis showed that the overall number of microbleeds detected by EPI-GRE, parallel-GRE, and conventional GRE was similar (p value > 0.05 for all) with 84.1% agreement by EPI-GRE and 93.4% by conventional GRE (Supplemental Table 5).

MRA

The presence or absence of stenosis in 12 intracranial arteries showed agreements of more than 80% between TOF-MRA and fast CE-MRA. Fast CE-MRA demonstrated a 77.9% agreement with TOF-MRA in both classifications (< 50% stenosis vs ≥ 50% stenosis and no stenosis vs < 50% stenosis vs ≥ 50% stenosis) (Table 4 and Fig. 5). Interobserver agreements between the two observers were greater than or equal to fair agreement (Supplemental Table 4).

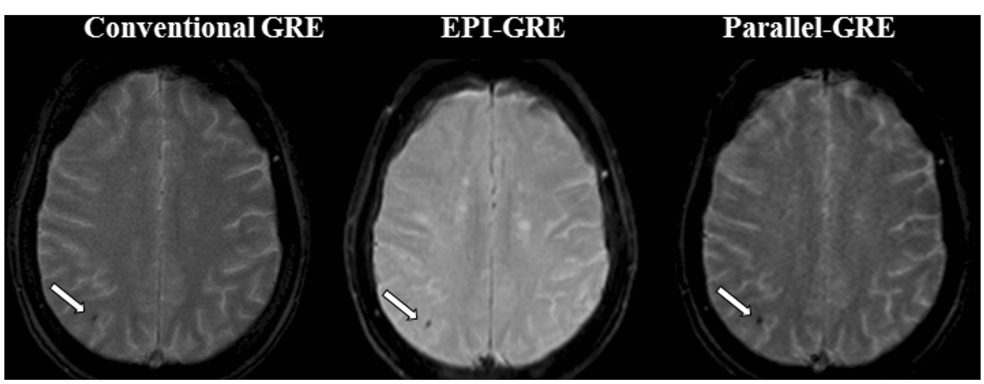

Fig. 4 Fast and conventional GRE. A microbleed in the right parietal lobe (arrows) is well demonstrated on both conventional GRE (right, scan time 141 s) and fast GRE (EPI-GRE [middle, scan time 29 s] and parallel-GRE [left, scan time 54 s])

Table 4 Agreement between fast CE-MRA and TOF-MRA and image quality between fast and conventional CE-MRA

	Fast CE-MRA	*p* value[†]
Agreement		
No stenosis versus stenosis	85.7% (0.824–0.891)	< 0.001
< 50% stenosis versus ≥ 50% stenosis	77.9% (0.741–0.816)	NA
No stenosis versus < 50% stenosis versus ≥ 50% stenosis	77.9% (0.741–0.816)	NA
Image quality		
Fast CE-MRA	2.9 ± 0.4 (1–4)	
Conventional CE-MRA (the same machine in other patients)	2.9 ± 0.4 (1–4)	> 0.05
Conventional CE-MRA (various machines in the same patients)	3.0 ± 0.4 (2–4)	> 0.05

Parentheses indicate one-sided 95% confidence intervals for agreement and range of scores for image quality

CE-MRA contrast-enhanced MR angiography

[†] Comparison between fast and conventional CE-MRA

Image quality did not differ for fast and conventional MRA sequences for conventional CE-MRA using the same machine on other patients and for conventional CE-MRA using different machines in the same patients (p value > 0.05).

Discussion

In this prospective study, fast MRI at 1.5 T is a reliable method for the detection and characterization of acute ischemic stroke and similar image quality in comparison with conventional MRI and achieved reductions in scan time of 38 to 79%. Therefore, fast MRI at 1.5 T is a reliable method to become a good alternative to conventional MRI.

Although the 6-min MRI protocol for acute ischemic stroke on a 3-T scanner suggested by Nael et al decreased the scan time and preserved diagnostic performance [2], 1.5-T scanners are generally more accessible than 3-T machines. The strategy for fast MRI on a 1.5-T scanner is simple and highly applicable and does not require advanced imaging methods. Therefore, with consideration of the generalizability and availability of the imaging modality, fast MRI using a 1.5-T scanner may be more suitable for acute ischemic stroke than sequences requiring a 3-T scanner.

We used simple methods to reduce the scan time, such as EPI and parallel imaging. Fast imaging inevitably leads to a downgrade in image quality. Thus, fast imaging requires a balance between the reduction of scan time and acceptable preservation of diagnostic performance; this requires a number of trials and validation studies. Despite the signal intensity ratio, apparent signal-to-noise ratio, and contrast-to-noise ratio being lower on fast MRI than on conventional FLAIR, our results showed that fast MRI is acceptable for evaluating patients with acute ischemic stroke. These relatively simple

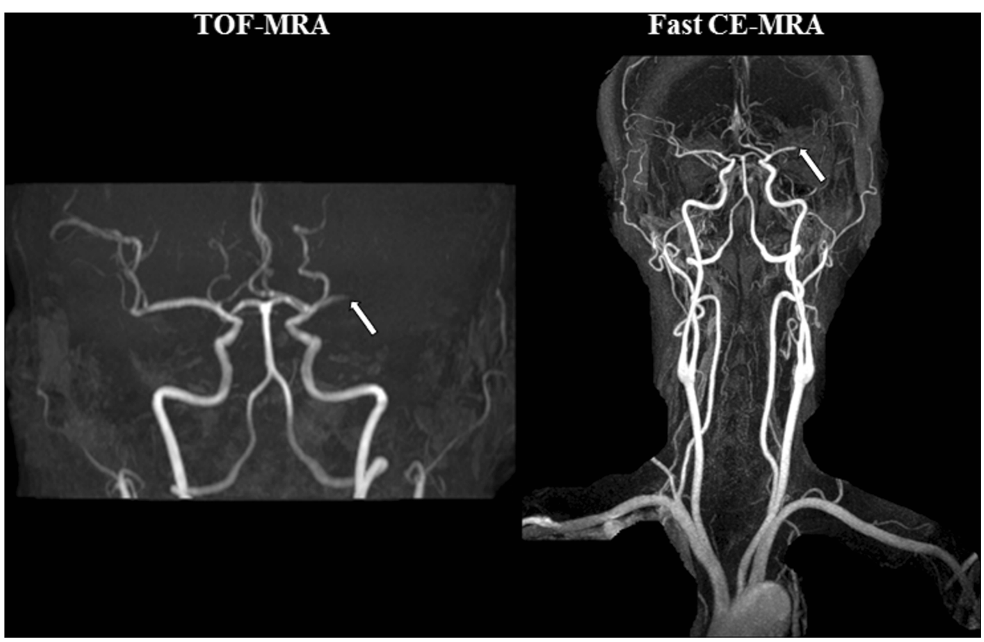

Fig. 5 Fast CE-MRA and TOF-MRA. Both TOF-MRA (right, scan time 274 s) and fast CE-MRA (left, scan time 39 s) nicely demonstrated an occlusion in the left proximal middle cerebral artery (arrows)

methods on a 1.5-T scanner can be tailored to different clinical settings. Evaluation by the fast MRI sequences EPI-FLAIR, EPI-GRE, and fast CE-MRA, with a total scan time of 113 s, may be useful in evaluating patients with a high probability of motion artifacts or when clinicians prefer the shortest scan time over the best image quality. By contrast, evaluation by other fast MRI sequences TR-FLAIR, parallel-GRE, and fast CE-MRA, with a relatively longer scan time of 172 s, may be an alternative to routine conventional MRI for acute stroke patients.

Nael et al postulated that EPI-FLAIR is feasible for the detection of acute ischemic hyperintensity on 1.5-T MRI [11]. They showed a concordance of 92% (24/26) for acute ischemic hyperintensity and 100% (5/5) for hyperintense vessels, whereas our EPI-FLAIR sequence showed a concordance of 82% (180/219) for acute ischemic hyperintensity and 7% (4/56) for hyperintense vessels. These discrepancies may be attributed to the different scoring systems and the sizes of the study populations. Nael et al used a dichotomic classification (concordant or discordant) for acute ischemic hyperintensity and hyperintense vessels, but we used a 3- or 4-scale scoring system. In this study, EPI-FLAIR was significantly inferior to ETL- and TR-FLAIR in the detection of acute ischemic hyperintensity and hyperintense vessels. Geometric distortion caused by magnetic field inhomogeneity and susceptibility artifacts in EPI-based sequences may also influence to the reduced detection rate of acute ischemic hyperintensity and hyperintense vessel signs in EPI-FLAIR [11]. Although EPI-FLAIR had the shortest scan time of the three fast FLAIR sequences, its diagnostic performance may be insufficient. Our results should be helpful in establishing the optimized combinations of fast MRI for individual institutions.

Although CT is the most common and efficient imaging modality for acute ischemic stroke, MRI is still an attractive modality, offering higher sensitivity for the detection of acute stroke (even when the infarct is small and located in the posterior fossa), more specific delineation of infarction core volume with clear discrimination of chronic ischemic lesions, and lack of exposure to ionizing radiation [3, 4, 21]. If the long scan times of MRI and its low availability for acute ischemic stroke can be overcome, MRI would be an excellent alternative to CT. A variety of imaging combinations could be established according to the individual institution, such as fast MRI with a highly accessible MR scanner or brain CT and CT angiography combined with some fast MRI sequences.

This study is subject to several limitations of note. First, this study was performed in a single referral center and with the arbitrary addition of fast MRI sequences to conventional MRI. Second, the three fast FLAIR sequences were not compared with conventional FLAIR within single acquisitions, because of long scan time-related ethical issues. The results may therefore be biased due to a clustering effect, even though a statistical correction was used. Third, we did not directly compare fast CE-MRA with conventional CE-MRA, because two injections of contrast media for CE-MRA would have been difficult to perform in the situation of real acute ischemic stroke; instead, we focused on the replacement of TOF-MRA with fast CE-MRA. Fourth, this study did not provide clinical implications, such as the time reduction to mechanical thrombectomy and improvement of clinical outcomes using fast MRI, as we focused on the reduction of scan time and preservation of diagnostic agreement. Further investigations are therefore warranted.

In conclusion, in comparison with conventional MRI, fast MRI at 1.5 T is a reliable method to detect and characterize acute ischemic stroke. Our results should be helpful to optimize acute stroke imaging in individual institutions.

Funding This study has received funding by the Korea Healthcare Technology R&D Project, Ministry for Health, Welfare & Family Affairs, Republic of Korea (HI12C1847).

Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Sang Joon Kim.

Conflict of interest The authors declare that they have no conflict of interest.

Statistics and biometry One of the authors (S Baek) has significant statistical expertise.

Informed consent Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
• Prospective
• Diagnostic study
• Performed at one institution

References

1. Kim BJ, Kang HG, Kim H-J et al (2014) Magnetic resonance imaging in acute ischemic stroke treatment. J Stroke 16:131
2. Nael K, Khan R, Choudhary G et al (2014) Six-minute magnetic resonance imaging protocol for evaluation of acute ischemic stroke: pushing the boundaries. Stroke 45:1985–1991
3. Warach S, Chien D, Li W, Ronthal M, Edelman RR (1992) Fast magnetic resonance diffusion-weighted imaging of acute human stroke. Neurology 42:1717–1723
4. Chalela JA, Kidwell CS, Nentwich LM et al (2007) Magnetic resonance imaging and computed tomography in emergency assessment of patients with suspected acute stroke: a prospective comparison. Lancet 369:293–298
5. Albers GW, Thijs VN, Wechsler L et al (2006) Magnetic resonance imaging profiles predict clinical response to early reperfusion: the

diffusion and perfusion imaging evaluation for understanding stroke evolution (DEFUSE) study. Ann Neurol 60:508–517
6. Davis SM, Donnan GA, Parsons MW et al (2008) Effects of alteplase beyond 3 h after stroke in the Echoplanar Imaging Thrombolytic Evaluation Trial (EPITHET): a placebo-controlled randomised trial. Lancet Neurol 7:299–309
7. Tong DC, Albers GW, Yenari MA, Marks MP (1999) A standardized MRI stroke protocol: comparison with CT in hyperacute intracerebral hemorrhage. Stroke 30:1974–1981
8. Badhiwala JH, Nassiri F, Alhazzani W et al (2015) Endovascular thrombectomy for acute ischemic stroke: a meta-analysis. JAMA 314:1832–1843
9. Lin Z, Guo Z, Qiu L, Yang W, Lin M (2016) The applied research of MRI with ASSET-EPI-FLAIR combined with 3D TOF MRA sequences in the assessment of patients with acute cerebral infarction. Acta Radiol 57:1515–1523
10. Korogi Y, Sugahara T, Shigematsu Y et al (1999) Ultrafast FLAIR imaging with single-shot echo-planar technique in evaluation of intracranial lesions. Comput Med Imaging Graph 23:119–126
11. Meshksar A, Villablanca JP, Khan R, Carmody R, Coull B, Nael K (2014) Role of EPI-FLAIR in patients with acute stroke: a comparative analysis with FLAIR. AJNR Am J Neuroradiol 35:878–883
12. Tomura N, Kato K, Takahashi S et al (2002) Comparison of multishot echo-planar fluid-attenuated inversion-recovery imaging with fast spin-echo fluid-attenuated inversion-recovery and T2-weighted imaging in depiction of white matter lesions. J Comput Assist Tomogr 26:810–814
13. Gai ND, Butman JA (2015) Reduced scan time 3D FLAIR using modulated inversion and repetition time. J Magn Reson Imaging 41:1440–1446
14. JM UK-I, Trivedi RA, Graves MJ et al (2005) Utility of an ultrafast magnetic resonance imaging protocol in recent and semi-recent strokes. J Neurol Neurosurg Psychiatry 76:1002–1005
15. von Elm E, Altman DG, Egger M, Pocock SJ, Gotzsche PC, Vandenbroucke JP (2007) Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. BMJ 335:806–808
16. Ebinger M, Galinovic I, Rozanski M, Brunecker P, Endres M, Fiebach JB (2010) Fluid-attenuated inversion recovery evolution within 12 hours from stroke onset: a reliable tissue clock? Stroke 41:250–255
17. Petkova M, Rodrigo S, Lamy C et al (2010) MR imaging helps predict time from symptom onset in patients with acute stroke: implications for patients with unknown onset time. Radiology 257:782–792
18. Yoshioka K, Ishibashi S, Shiraishi A, Yokota T, Mizusawa H (2013) Distal hyperintense vessels on FLAIR images predict large-artery stenosis in patients with transient ischemic attack. Neuroradiology 55:165–169
19. Wardlaw JM, Smith EE, Biessels GJ et al (2013) Neuroimaging standards for research into small vessel disease and its contribution to ageing and neurodegeneration. Lancet Neurol 12:822–838
20. Arnould M-C, Grandin CB, Peeters A, Cosnard G, Duprez TP (2004) Comparison of CT and three MR sequences for detecting and categorizing early (48 hours) hemorrhagic transformation in hyperacute ischemic stroke. AJNR Am J Neuroradiol 25:939–944
21. Vert C, Parra-Farinas C, Rovira A (2017) MR imaging in hyperacute ischemic stroke. Eur J Radiol. https://doi.org/10.1016/j.ejrad.2017.06.013