pISSN 2384-1095
eISSN 2384-1109

iMRI 2021;25:81-92

https://doi.org/10.13104/imri.2021.25.2.81

iMRI
Investigative Magnetic Resonance Imaging

Fast MRI in Acute Ischemic Stroke: Applications of MRI Acceleration Techniques for MR-Based Comprehensive Stroke Imaging

Sung-Hye You, Byungjun Kim, Bo Kyu Kim, Sang Eun Park

Department of Radiology, Anam Hospital, Korea University College of Medicine, Seoul, Korea

The role of neuroimaging in patients with acute ischemic stroke has been gradually increasing. The ultimate goal of stroke imaging is to make a streamlined imaging workflow for safe and efficient treatment based on optimized patient selection. In the era of multimodal comprehensive imaging in strokes, imaging based on computed tomography (CT) has been preferred for use in acute ischemic stroke, because, despite the unique strengths of magnetic resonance imaging (MRI), MRI has a longer scan duration than does CT-based imaging. However, recent improvements, such as multicoil technology and novel MRI acceleration techniques, including parallel imaging, simultaneous multi-section imaging, and compressed sensing, highlight the potential of comprehensive MR-based imaging for strokes. In this review, we discuss the role of stroke imaging in acute ischemic stroke management, as well as the strengths and limitations of MR-based imaging. Given these concepts, we review the current MR acceleration techniques that could be applied to stroke imaging and provide an overview of the previous research on each essential sequence: diffusion-weighted imaging, gradient-echo, fluid-attenuated inversion recovery, contrast-enhanced MR angiography, and MR perfusion imaging.

Keywords: Stroke; Magnetic resonance imaging; Acceleration

Review Article

Received: February 28, 2021
Revised: April 6, 2021
Accepted: April 7, 2021

Correspondence to:
Byungjun Kim, M.D., Ph.D.
Department of Radiology, Anam Hospital, Korea University College of Medicine, 73, Goryeodae-ro, Seongbuk-gu, Seoul 02841, Korea.
Tel. +82-2-920-5567
Fax. +82-2-929-3796
E-mail: cardillo@hanmail.net

INTRODUCTION

The role of neuroimaging in patients with acute ischemic stroke has been gradually increasing. The ultimate goal of stroke imaging is to make a streamlined imaging workflow for safe and efficient treatment based on optimized patient selection. The rapid delivery of intravenous thrombolytics within 4.5 h of the time of onset has been the most important treatment goal in patients with acute ischemic stroke. Parenchymal imaging using non-contrast brain computed tomography (CT) or diffusion-weighted imaging (DWI) is used to exclude intracranial hemorrhage and extensive infarction (Table 1). With advances in neuro-interventional therapy, the effectiveness of mechanical thrombectomy done early (< 6 h from symptom onset) in patients with large-vessel occlusion was verified by means of six randomized trials in 2015 (1-6); hence CT or magnetic resonance (MR) angiography (MRA) was added as a standard imaging protocol for strokes to find large-vessel occlusion (occlusion in the intracranial internal

Table 1. Role of Imaging in Patients with Acute Ischemic Stroke according to the Type of Treatment, Imaging Modality, and Time from Onset of Symptoms

Treatment	Time from symptom onset	CT-based protocol	MR-based protocol	Role of imaging	Indication for treatment	Contraindication for treatment
IV thrombolysis	< 4.5 h	Head CT (non-CE)	DWI	Diagnosis of acute ischemic infarction Define the extent of core infarction		Extensive infarction (>1/3 of MCA territory)
			GRE	Exclusion of intracranial hemorrhage		Acute intracranial hemorrhage
	Unknown stroke onset		DWI-FLAIR	Deduction of onset time via DWI-FLAIR mismatch - DWI (+) and FLAIR (-): onset of symptoms less than 4.5 h	Mismatch (+)	
Mechanical thrombectomy	Early time window (< 6 h)	Head CT (non-CE)	DWI	Diagnosis of acute ischemic infarction Define the extent of core infarction	ASPECT score ≥ 6	
			GRE	Exclusion of intracranial hemorrhage		Acute intracranial hemorrhage
		CTA	CE-MRA	Demonstrate large vessel (intracranial ICA and M1) occlusion	Large vessel occlusion	
	Late time window (6-24 h) or unknown	Head CT (non-CE)	DWI	Diagnosis of acute ischemic infarction Define the extent of core infarction	ASPECT score ≥ 6	
			GRE	Exclusion of intracranial hemorrhage		Acute intracranial hemorrhage
		CTA	CE-MRA	Demonstrate large vessel (intracranial ICA and M1) occlusion	Large vessel occlusion	
		CT perfusion	MR perfusion	Guiding late-window thrombectomy Evaluate salvageable tissue (core-penumbra mismatch) - Ischemic core: relative CBF reduction greater than 30% of normal CBF - Ischemic penumbra: T_{max} (time to max) > 6 s	Mismatch (+)	
		Multiphase CTA	Time-resolved CE-MRA	Guiding late-window thrombectomy Predict fast versus slow progression		

ADC = apparent diffusion coefficient; CBF = cerebral blood volume; CE-MRA = contrast-enhanced magnetic resonance angiography; CT = computed tomography; CTA = computed tomography angiography; DWI = diffusion-weighted imaging; FLAIR = fluid-attenuated inversion recovery; GRE = gradient-echo; ICA = internal carotid artery; M1 = proximal middle cranial artery; MR = magnetic resonance

carotid artery or proximal middle cranial artery). Thereafter, two follow-up studies in 2018 revealed the usefulness of mechanical thrombectomy in the later window (6-24 h from symptom onset) (7, 8); hence, the importance of perfusion imaging for evaluating salvageable tissue using the T_{max} index has received attention. In addition, several recent studies have attempted to demonstrate the role of collateral imaging based on multiphase CT or MRA in predicting the speed of infarct progression (9-12).

In the era of multimodal comprehensive imaging in strokes, CT-based imaging has been preferentially used in acute ischemic stroke, despite the unique strengths of MRI. A major limitation of MRI is the scan duration of approximately 20 min, which is longer than that of CT-based imaging. However, over the last decade, improvements in hardware and the development of various novel imaging techniques, such as parallel imaging, simultaneous multi-section (SMS) imaging, and compressed sensing, have speeded up acquisition, thereby enabling the use of MR-based protocols in comprehensive stroke centers (13). In this review, we discuss the current state of the art of acceleration techniques and provide an overview of the major research efforts focused on their application to each essential sequence of stroke imaging. Radiologists, neurologists, and other physicians who manage stroke patients should be familiar with these new techniques and establish the optimal imaging protocols for their stroke centers.

Advantages of MR-Based Stroke Imaging

Currently, CT is accepted as the most effective imaging modality for evaluating patients with an acute ischemic

stroke because of its distinctive advantages over MRI, such as its widespread availability, cost effectiveness, and rapid acquisition time (Table 2). However, radiation hazards are inevitable in CT, because the dose of radiation during a comprehensive CT protocol for stroke is approximately six times that of an unenhanced head CT (14). Moreover, as a parenchymal imaging modality, CT is not sensitive in detecting small infarcts. In addition, a post-processing program is required to calculate the core infarct volume in CT perfusion imaging.

In contrast, MRI-based stroke imaging has several characteristic advantages over CT. First, DWI has the highest sensitivity for detecting acute ischemia, even if it is small and located in the posterior circulation. For the measurement of the infarct volume, which is important for excluding extensive infarction and calculating the volume of salvageable tissue in the later time window, DWI is the most accurate sequence for delineating the core infarct volume without a specific post-processing program (9). Moreover, selecting patients for mechanical thrombectomy based on the calculated core infarct volume (< 70 mL in the early time window) using DWI has been associated with favorable outcomes (15, 16).

Second, in patients with an unknown onset time (mostly wake-up stroke patients), who account for approximately 20% of acute ischemic stroke cases (17, 18), the onset time can be approximated using DWI-fluid-attenuated inversion recovery (DWI-FLAIR) mismatch, as was shown by several studies that revealed the onset time in DWI (+)-FLAIR (-) patients to be 3 to 4.5 h (19-21). Thus, some patients who are excluded based on the selection criteria for CT-based evaluation can be included for intravenous thrombolysis and have a significantly better functional outcome (19, 21).

Finally, MRI works much better for evaluating stroke-mimicking conditions, which have been reported in approximately 17% of patients, even at the most advanced stroke centers (22). The accurate diagnosis of stroke-mimicking conditions, such as seizures, migraines, neoplasms, venous infarctions, and the posterior reversible encephalopathy syndrome, is important in order to avoid unnecessary acute treatment, but this is challenging under the CT-based protocol (23, 24).

Value of Fast Imaging in Acute Ischemic Stroke

The goal of establishing an optimal stroke protocol is to balance the amount of information obtained from the images against the time spent obtaining the images. Minimizing the workflow duration is important for acute ischemic stroke, because the outcome of stroke management strongly depends on the onset-to-recanalization time. In addition, rapid imaging is crucial in patients with stroke, because many patients with acute ischemic stroke are uncooperative and cannot tolerate long scan times, which could result in severe motion artifacts (13).

Two recent trials (THRACE and GOLIATH) compared the efficacy of CT- and MR-based protocols for patient selection and concluded that the MR-based imaging protocol was not inferior to the CT-based protocol (14, 25). In these trials, the total imaging acquisition times were 13 and 11 min, respectively. The longer imaging time of the MR-based protocol was not associated with a worse functional outcome for acute ischemic stroke. However, considering that not all comprehensive MR sequences were included in the aforementioned two studies and that the total acquisition time for the comprehensive CT protocol, including CT/CT angiography/CT perfusion, was approximately 10 min, rapid imaging remains an open

Table 2. Comparisons between CT and MR-Based Imaging Protocols for Acute Ischemic Stroke

	CT-based protocol	MR-based protocol
Advantages	- Widespread availability - Speed of acquisition - Cost effectiveness	- Accurate assessment of core infarction via DWI (both detection and volume measurement) * Sensitive to the detection of acute ischemia * Specific for delineation of the infarction core volume - Deduction of onset time in wake-up stroke - Accurate diagnosis of stroke mimics - Lack of radiation
Disadvantages	- Radiation - Requirement of post-processing to evaluate infarct core - Relatively low sensitivity for acute ischemic infarction	- Limited availability - Longer acquisition time - Delayed workflow related to required patient screening for contraindication

CT = computed tomography; DWI = diffusion-weighted imaging; MR = magnetic resonance

challenge for MRI-based imaging (14).

MRI Acceleration Techniques

The recent advances in MRI technology largely aim to speed up acquisition. The current improvements in multicoil technology and the commercialization of stronger magnetic fields enable several newly developed fast-imaging tools to be applied in daily practice while maintaining sufficient imaging quality. In the following paragraphs, we briefly discuss the principles, key elements, advantages, and disadvantages of MRI acceleration techniques for stroke imaging. The key characteristics of each technique are presented in Table 3.

Echo-Planar Imaging (EPI)

EPI is the classic fast-imaging technique, wherein the entire k-space is filled with a radiofrequency (RF) pulse (single-shot EPI) (26). The rapid gradient switching enables each MR slice to be acquired within 50-100 ms (26). Currently, the techniques that fill the entire k-space with a few RF pulses are also classified as EPI sequences (multi-shot EPI). The echo train length (ETL), also referred to as the EPI factor by Siemens and Philips, is defined as the number of k-space lines encoded in a single shot. Thus, in single-shot EPI, the number of phase-encoding steps is equal to the ETL, and in multi-shot EPI, the ETL is a key parameter for determining the acquisition speed. The main strength of single-shot EPI is that it can be done with most MR scanners regardless of their type or vendor. However, geometric distortion and susceptibility artifacts are the limitations of the EPI technique. Fortunately, the combination of EPI and parallel imaging can partially solve these issues (27). The main sequences that apply this technique are diffusion, perfusion, and functional MRI. For stroke imaging, EPI has been applied in DWI, gradient-echo (GRE), FLAIR, and MR perfusion imaging (dynamic susceptibility contrast MRI) (26). FLAIR-like echo-planar images can also be obtained using inversion pulses.

Parallel Imaging

The EPI technique enables fast imaging, but the rapid gradient change can cause problems, such as high-level acoustic noise and magnetic burden. Parallel imaging can solve these problems, because it was developed to target a reconstruction step (28). In this technique, rapid acquisition is achieved by means of k-space undersampling in the phase-encoding direction, and the problem caused by undersampling (aliasing artifacts) is solved by means of creative reconstruction that uses positional information derived from a multichannel phased-array coil (29). Originally, multiple small receiver coils were developed to reduce noise and increase the signal-to-noise ratio (SNR). Several overlapping small coils can cover the volume of one large coil; when information from all the small coils is summed, the noise decreases, and the SNR increases. However, in parallel imaging, positional information from the multichannel phased-array coil is used to supplement the insufficient k-space information. For example, if several coils are placed around the head, the strength of the signal from a specific location depends on its proximity to the coil. By considering the coil position and estimating the location of the signal, one can create a position map, that is, a coil sensitivity map in image domain reconstruction and autocalibration signal data in k-space domain reconstruction (28, 29).

There are two different reconstruction methods in parallel imaging (Table 4). The first is image domain reconstruction, which generates unfolded images using a coil-sensitivity map from the aliased image derived from the undersampled k-space (reconstruct and then correct) (28). The other is k-space domain reconstruction, wherein the undersampled k-space is filled using autocalibration signal data before Fourier transformation (correct and then reconstruct) (28). The former provides a slightly higher SNR and is more appropriate for small homogeneous body regions, such as the brain, whereas the latter is more advantageous for combination with the EPI technique. Presently, both methods are actively applied in neuroimaging.

The main advantage of parallel imaging is that it speeds up image acquisition. The parameter for speed is the parallel imaging acceleration factor (the amount of k-space data required for a fully sampled image/amount of k-space data actually acquired). The most common commercially available acceleration factor range is 1.5 to 4 (28). Another advantage of parallel imaging is its wide applicability. Theoretically, parallel imaging can be applied to all types of pulse sequences and can be easily combined with other fast-imaging methods.

SMS Imaging

The technical principle of SMS imaging is multi-section excitation in a single repetition time using multiband RF

https://doi.org/10.13104/imri.2021.25.2.81

Table 3. MRI Acceleration Techniques for Stroke Imaging

Techniques	Description	Category	Siemens	Philips	GE	Key element	Parameter for speed	Typical acquisition acceleration	Representative applicable pulse sequences	Advantage	Drawback
EPI	One of the most traditional fast imaging techniques using rapid gradient switching	Single-shot EPI Multi-shot EPI					ETL		DWI PWI	Rapid acquisition widespread availability	Geometric distortion
Parallel imaging	MRI techniques removing aliasing artifacts from the k-space undersampling	Imaging domain reconstruction-based technique	mSENSE (sensitivity encoding)	SENSE	ASSET	Multichannel phased-array coil Coil sensitivity map	Parallel imaging acceleration factor	1.5-4 times	Almost any pulse sequences	Reduction in image acquisition time Reduction in susceptibility artifacts	Reduction in SNR PI-related artifacts
		k-space domain reconstruction-based technique	GRAPPA		ARC imaging	ACS Weighting factors					
SMS imaging	MR technique using a multiband radiofrequency pulse that excites protons in multiple sections in a single repetition time		SMS	Multi-band SENSE	Hyperband		Section acceleration factor	2-8 times	DWI, DTI, functional MRI	Reduction in image acquisition time	Artifacts (residual aliasing and/or section leakage, Nyquist-like ghosts)
CS	Rapid imaging technique based on semi-random, incomplete sampling of k-space		GRASP-VIBE	Compressed SENSE	Hyper-SENSE	Sparsity Incoherence Iterative nonlinear reconstitution	CS acceleration factor		3D-FLAIR 3D-T1WI	Reduction in image acquisition time	Long reconstruction time

ACS = autocalibration signal data; ARC = autocalibrating reconstruction for Cartesian; CS = compressed sensing; DTI = diffusion tensor imaging; DWI = diffusion-weighted imaging; EPI = echo-planar imaging; ETL = echo train length; FLAIR = fluid-attenuated inversion recovery; GRAPPA = generalized autocalibrating partial parallel acquisition; PI = parallel imaging; PWI = perfusion-weighted imaging; SMS = simultaneous multi-section; SNR = signal-to-noise ratio

Table 4. Comparison of Two Parallel Imaging Techniques

	Imaging domain reconstruction-based technique	k-space domain reconstruction-based technique
Acronyms	mSENSE SENSE ASSET	GRAPPA ARC
Method	Reconstruct and then correct	Correct and then reconstruct
Total imaging time		Somewhat longer (extra time for self-calibration)
Signal-to-noise	Slightly higher SNR and better image quality	
Body region	Brain (poor in heterogenous body region; accurate coil sensitivity maps might be difficult to obtain)	Lung, abdomen, MSK
FOV	May produce aliasing in the phase-encode direction if the full FOV is smaller than the imaged object	Tolerant to small FOV
Use with echo-planar image		Better Less susceptibility-induced field distortion

FOV = field of view; MSK = musculoskeletal; SNR = signal-to-noise ratio

pulses (30, 31). Accelerated imaging can be achieved by means of the simultaneous acquisition of signals from such slices. The speed parameter in SMS imaging is the section acceleration factor, that is, the number of simultaneously acquired slices. The commercially used acceleration factors range from 2 to 8. Currently, acceleration factors of 2 to 4 can be achieved without SNR loss. The major sequences that use this method are DWI, diffusion tensor imaging, and functional MRI (28).

Compressed Sensing (CS)

CS is a rapid-imaging technique with semi-random and incomplete k-space sampling. The three main principles of CS are sparsity, incoherence, and iterative nonlinear reconstruction (28). The basic concept of this method is that full data are not required to compose an image. For example, in a dynamic image, very few images change. Even if the data from a normal photo are compressed ten-fold, the quality of the photo is not significantly different to the eye if the background is of zero intensity or the color of one part is similar to that of an adjacent part. Based on this concept, the k-space data are randomly undersampled to avoid coherent artifacts. However, a problem arises when complete random sampling is done, because essential information exists in the central k-space. Thus, semi-random acquisition of data, with preferential sampling of the k-space center, is done. Then, incoherent artifacts are eliminated via iterative nonlinear reconstruction. The critical challenge of applying CS to stroke imaging is the long computation time (usually > 30 min) (28). A few previous studies on routine neuro- and cardiac imaging have demonstrated the utility of CS in 3D-FLAIR, 3D-T1WI, and cardiac CINE imaging (32-34). Further technical improvements are necessary to enable the use of CS for stroke imaging.

Application of MR Acceleration Techniques for Each MRI Sequence in Stroke Imaging

A comprehensive MR-based imaging protocol for stroke should include five sequences: DWI, T2* imaging, FLAIR, MRA, and MR perfusion. The role of each sequence is summarized in Table 1. For each sequence, many studies have attempted to find the most suitable imaging parameters using the fast MR techniques described above (27, 35-45) (Table 5). Although there is neither a standard guideline for optimal parameters or methods for each sequence in patients with acute ischemic stroke nor any consistent criteria for selecting the better image, a review of previous research could provide a basis for future multicenter prospective trials and standard clinical guidelines.

DWI

In general, DWI is done using single-shot EPI, and parallel imaging is combined to accelerate the scan time. For the type of parallel imaging, studies conducted in the 2000s used image domain reconstruction techniques (SENSE and

https://doi.org/10.13104/imri.2021.25.2.81

Table 5. Summary of Previous Studies Applying Fast MRI Techniques to Patients with Acute Ischemic Stroke

Sequences	Role	Author, year	Number of patients	Method	Acceleration factor	Total acquisition time	Thickness	Field strength	Image quality	Note
DWI	Most sensitive imaging sequence for assessing the ischemic core.	Willinek et al., 2003 (35)	27	EPI, PI (SENSE)	2	47 s	5 mm	1.5T	Acceptable	SS-EPI
		U King-Im et al., 2005 (36)	23	EPI, PI (ASSET)	2	39 s	4 or 5 mm	1.5T	Acceptable	SS-EPI
		Nael et al., 2014 (37)	62	EPI, PI (GRAPPA)	3	58 s	4 mm	3.0T	Feasible	SS-EPI
		Prakkamakul et al., 2016 (38)	59	EPI, PI (GRAPPA)	3	1 min 20 s	5 mm	3.0T	High diagnostic concordance with conventional protocol	SS-EPI
		Skare et al., 2018 (40)	N/A	EPI, PI (GRAPPA)	3	15 s	4 mm	1.5 or 3.0T	Acceptable	SS-EPI
		Ryu et al., 2019 (39)	25	EPI, PI (ARC) and SMS (hyperband)	2 (PI)*	13 s	5 mm	3.0T	Acceptable	SS-EPI
GRE	Detecting acute intracranial hemorrhage	Nael et al., 2014 (37)	62	EPI, PI (GRAPPA)	3	56 s	4 mm	3.0T	Feasible	EPI-GRE
		Skare et al., 2018 (40)	N/A	EPI, PI (GRAPPA)	3	6 s	4 mm	1.5 or 3.0T	Acceptable	EPI-GRE
		Ryu et al., 2019 (39)	25	EPI, PI (ASSET)	3	6 s	5 mm	3.0T	Acceptable	EPI-GRE
		Chung et al., 2019 (27)	380	SS-EPI, PI (GRAPPA)	2	29 s	5 mm	1.5T	Parallel-GRE > EPI-GRE	EPI-GRE
				PI (GRAPPA)	3	54 s	5 mm	1.5T		Parallel-GRE
FLAIR	FLAIR-DWI mismatch	Willinek et al., 2003 (35)	62	PI (SENSE)	2	35 s	5 mm	1.5T	Acceptable	
		U King-Im et al., 2005 (36)	23	PI (ASSET)	2	44 s	4 or 5 mm	1.5T	Acceptable	
		Nael et al., 2014 (37)	62	EPI, PI (GRAPPA)	3	52 s	4 mm	3.0T	Feasible	EPI-FLAIR
		Meshksar et al., 2014 (41)	52	EPI, PI (GRAPPA)	2	52 s	5 mm	1.5T	Feasible	
		Prakkamakul et al., 2016 (38)	59	PI (GRAPPA)	2	1 min 36 s	5 mm	3.0T	High diagnostic concordance with conventional protocol	FSE
		Skare et al., 2018 (40)	N/A	EPI, PI (GRAPPA)	3	24 s	4 mm	1.5 or 3.0T	Acceptable	EPI-FLAIR
		Ryu et al., 2019 (39)	25	EPI, PI (ARC)	2	25 s	5 mm	3.0T	Acceptable	EPI-FLAIR
		Chung et al., 2019 (27)	482	EPI, PI (GRAPPA)	2	45 s	5 mm	1.5 or 3.0T	ETL-FLAIR, TR-FLAIR > EPI-FLAIR	EPI-FLAIR
				Increased ETL (32), PI (GRAPPA)	2	74 s	5 mm	1.5 or 3.0T		ETL-FLAIR (increased ETL, 32)
				Decreased TR (9000 -> 5560), PI (GRAPPA)	2	79 s	5 mm	1.5 or 3.0T		TR-FLAIR (decreased TR)
		Vranic et al., 2019 (32)	66	CS-PI (SENSE)	3.4	3 min 36 s	N/A	3.0T	Similar to conventional imaging	3D-FLAIR
		Delattre et al., 2020 (33)	19	CS	5.3	4 min	N/A	3.0T	Only minor penalty in image quality	3D-FLAIR

Continued

Table 5. Continued

Sequences	Role	Author, year	Number of patients	Method	Acceleration factor	Total acquisition time	Thickness	Field strength	Image quality	Note
MRA	Assessment of large vessel occlusion	U King-Im et al., 2005 (36)	23	PI (ASSET)	2	54 s		1.5T	Acceptable	TOF-MRA
		Boujan et al., 2018 (42)	123	TOF-MRA		3 min 7 s		3.0T	CE-MRA > TOF MRA (time and coverage)	TOF-MRA
				CE-MRA		64 s		3.0T		CE-MRA
		Nael et al., 2014 (37)	62	PI (GRAPPA)	4	22 s		3.0T	Feasible	CE-MRA
	Assessment of collaterality via time-resolved MRA	Chung et al., 2019 (27)	190	PI (GRAPPA)	3	39 s		1.5T	Acceptable	CE-MRA
		Le Bras et al., 2015 (43)	32	BLAST		1 min 44 s		3.0T		TR CE-MRA (No. of dynamics 12)
		Bak et al., 2017 (44)	462	TRICK				3.0T		TR CE-MRA (temporal resolution 2.5 s), TRICK
MR Perfusion	Estimating the penumbra	Nael et al., 2014 (37)	62	PI (GRAPPA)	3	90 s	4 mm	3.0T	Feasible	DSC-MRI
		Chakhoyan et al., 2018 (45)	13	PI (GRAPPA) + SMS	8 (PI FA 2, SMS FA 4)	90 s	5 mm	3.0T	Increased spatiotemporal resolution	DSC-MR Temporal resolution, 0.75 s

* No information on the section acceleration factor.

ARC = autocalibrating reconstruction for Cartesian; BLAST = broad-use linear acquisition speed-up technique; CE-MRA = contrast-enhanced magnetic resonance angiography; CS = compressed sensing; DSC = dynamic susceptibility contrast; DWI = diffusion-weighted imaging; EPI = echo-planar imaging; FLAIR = fluid-attenuated inversion recovery; FSE = fast spin echo; GRAPPA = generalized autocalibrating partial parallel acquisition; GRE = gradient-echo; MR = magnetic resonance; MRI = magnetic resonance imaging; PI = parallel imaging; SMS = simultaneous multi-section; SS = single-shot; TOF = time-of-flight; TR = repetition time; TRICK = time-resolved imaging for contrast kinetics

ASSET) (35, 36), but generalized autocalibrating partial parallel acquisition (GRAPPA), with an acceleration factor of 3, is recently being adopted more commonly (37, 38, 40). A recent study on the clinical feasibility of 1-min ultrafast brain MRI using a combination of EPI, parallel imaging (autocalibrating reconstruction for Cartesian imaging), and SMS (hyperband) (acquisition time of 13 s) reported an inferior, but at least acceptable, image quality comparable to that of conventional protocols (40). Although there is no consensus on the optimal acceleration factor for a balance between speed and image quality, a combination of EPI, parallel imaging, and SMS might be the main pivot for DWI in acute ischemic stroke.

T2 Image*

T2* images are fundamentally EPI-based images, and parallel imaging with k-space domain reconstruction is usually combined with them to increase the scan speed. In addition to increasing the speed, geometric distortion can be improved by adding parallel imaging (37, 39, 40). However, a recent study that compared EPI + parallel imaging (EPI-GRE) to parallel imaging alone with a high acceleration factor (R = 3) (parallel-GRE) revealed that parallel-GRE works better than EPI-GRE does in detecting the susceptibility vessel sign, delineating microbleeds, and finding hemorrhagic transformation, even though the scan time was shorter for EPI-GRE (29 s vs. 54 s) (27). Although EPI-GRE with parallel imaging might be a basic method, further studies focusing on stroke-specific imaging criteria, such as the accuracy of detecting a susceptibility vessel sign or hemorrhagic transformation, should be conducted.

FLAIR

For FLAIR, the mainstream of fast imaging is changed from imaging domain parallel imaging, such as SENSE, to EPI with k-space domain parallel imaging (generalized autocalibrating partial parallel acquisition). Using the EPI + parallel imaging method, with an acceleration factor of 2 or 3, one can acquire FLAIR images within 30 to 60 s. However, there is controversy over the superiority of EPI-FLAIR. Chung et al. (27) reported that FLAIR with increased ETL (ETL-FLAIR) and FLAIR with decreased repetition time (TR-FLAIR) were significantly better than EPI-FLAIR in detecting acute ischemic hyperintensity and hyperintense vessels. The value of this study was its evaluation of stroke-specific imaging factors instead of using a general Likert scale. Thus, like GRE, although EPI-FLAIR is commonly used in many stroke centers, future multicenter studies are warranted.

MRA

For the optimal sequence, the superiority of contrast-enhanced MRA (CE-MRA), when compared to time-of-flight MRA (TOF-MRA), which results from its large field of view and short scan time, has been demonstrated in previous studies (42, 43). The role of fast-imaging methods is different in CE-MRA from that in parenchymal imaging or TOF-MRA. There is little room for reducing the total acquisition time in CE-MRA, because the image must be obtained during the arterial phase. Instead, improving the temporal and spatial resolution using fast-imaging methods is the main issue in MRA.

The primary goal for doing MRA in patients with acute ischemic stroke is to diagnose large-vessel occlusion; the secondary one is to evaluate collaterality. For the primary goal, single-phase CE-MRA is sufficient, but the importance of collateral imaging in the extended time window for mechanical thrombectomy is gradually increasing. Thus, the main issue in MRA is whether to choose single-phase CE-MRA or time-resolved CE-MRA. With the improvement of rapid MRI techniques, time-resolved MRA can be done with a good temporal resolution of a few seconds (46). The time saved in parallel imaging or CS with high acceleration factors (> 4) could be used to improve the spatial resolution (47), because the main problem in time-resolved CE-MRA is the low spatial resolution. Recently, radial k-space sampling schemes have been used for dynamic CE-MRA (Siemens, TWIST; Philips, 4D-TRAK; GE, TRICK), and they have shown feasible diagnostic quality for intracranial and neck vascular structures. Although single-phase MRA is sufficient in patients with an early time window, further investigation to improve the image quality of time-resolved CE-MRA using fast-imaging methods might be required for collaterality evaluation.

MR Perfusion Imaging

Perfusion MRI could be included in the comprehensive stroke protocol to evaluate the volume of salvageable tissue in patients in the late time window. Dynamic susceptibility contrast MRI (DSC-MRI) is the most widely used MRI technique for assessing the cerebral hemodynamic state (48). Gradient-echo single-shot EPI DSC-MRI, with a total acquisition time of approximately 90 s, is a commonly used imaging sequence for stroke, but there is no way to reduce the total scan time further (48). Instead, by applying rapid imaging methods, such as parallel imaging, SMS imaging, or CS, better spatial resolution can be achieved, which is important for accurate post-processing of hemodynamic parameters. A good spatiotemporal resolution is a key factor for obtaining an accurate arterial input function. A recent study that used parallel and SMS imaging in DSC-MRI reported improved spatiotemporal resolution (45). Future studies should focus on the spatial resolution of DSC-MRI using MRI acceleration techniques.

Future Perspectives on Fast MRI for Acute Ischemic Stroke

In 2014, Nael et al. (37) proposed a 6-min MR-based comprehensive stroke protocol including DWI, GRE, FLAIR, CE-MRA, and DSC-MRI, which was developed using EPI and parallel imaging. This has been a good landmark for daily practice and follow-up research (Table 6). Although three other trials (14, 25, 49) demonstrated the feasibility of the MR-based protocol for stroke (total acquisition times were 15, 11, and 13 min, respectively), not all sequences were included in those studies. In future research, to optimize the MR-based stroke protocol, it is necessary to consider the following points:

1) the sequences that should be included in the stroke

Table 6. Summary of Studies on MR-Based Stroke Protocols

Trials	Author, year	Number of patients	Sequences	Total acquisition time
6-min brain MRI	Nael et al., 2014 (37)	62	FLAIR, DWI, GRE, CE-MRA, PWI (DSC) [EPI + PI protocol]	6 min
SMART trial	Shah et al., 2015 (49)	157	FLAIR, DWI, TOF-MRA, PWI (DSC)	15 min
GOLIATH trial	Simonsen et al., 2018 (25)	128	FLAIR, DWI, GRE, TOF-MRA	11 min
THRACE trial	Provost et al., 2019 (14)	299	No standardized imaging acquisition Included at least brain DWI and MRA	13 min

CE-MRA = contrast-enhanced magnetic resonance angiography; DSC = dynamic-susceptibility contrast; DWI = diffusion-weighted imaging; EPI = echo-planar imaging; ETL = echo train length; FLAIR = fluid-attenuated inversion recovery; GOLIATH = general or local anesthesia in intra-arterial therapy; GRE = gradient-echo; MR = magnetic resonance; MRI = magnetic resonance imaging; PI = parallel imaging; PWI = perfusion-weighted imaging; SMART = screening with MRI for accurate and rapid stroke treatment; THRACE = thrombectomie des artères cérébrales; TOF = time-of-flight

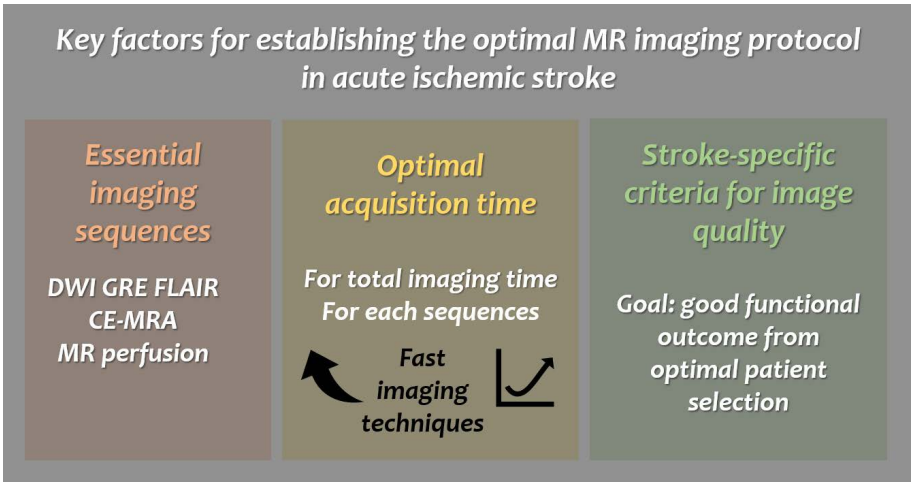

Fig. 1. Key factors for establishing the optimal MR imaging protocol for acute ischemic stroke. CE-MRA = contrast-enhanced magnetic resonance angiography; DWI = diffusion-weighted imaging; FLAIR = fluid-attenuated inversion recovery; GRE = gradient-echo; MR = magnetic resonance

protocol,

2) the appropriate imaging acquisition time for each sequence and the entire imaging, and
3) the stroke-specific imaging criteria for evaluating the feasibility of the new sequence (Fig. 1).

As essential sequences, we believe that the inclusion of DWI, GRE, FLAIR, MRA, and MR perfusion is ideal for establishing a standard protocol, although MR perfusion could be skipped in clinical practice. For the total acquisition time, a reasonable maximum time that is not inferior to the CT-based protocol is approximately 10 min (14). However, considering the motion artifacts, each sequence must be done as quickly as possible while maintaining sufficient imaging quality. A noteworthy point about this issue is that sufficient imaging quality is defined slightly differently for stroke imaging than in its general concept. For example, an imaging quality that is suitable for detecting large-vessel occlusion is sufficient in single-phase CE-MRA, and the resolution of the distal vessel is not important in acute stroke imaging. Thus, the evaluation criteria should be redefined for acute ischemic stroke. Specific imaging criteria, such as the detection rate of ischemic change, accuracy in the calculation of infarct volume, and detection of large-vessel occlusion, are more meaningful than are general Likert-scale ratings, such as poor, acceptable, or good. In addition, from a clinical perspective, improving the functional outcomes after management could be an important criterion for evaluating the usefulness of imaging protocols for stroke.

In the future, many studies may evaluate the optimal imaging protocol for stroke, and knowledge of fast-imaging techniques is important for this work. Radiologists should be familiar with fast-imaging techniques, as well as the role of stroke imaging, and take the lead in establishing the optimal imaging protocol for their stroke centers.

REFERENCES

1. Berkhemer OA, Fransen PS, Beumer D, et al. A randomized trial of intraarterial treatment for acute ischemic stroke. N Engl J Med 2015;372(1):11-20
2. Goyal M, Demchuk AM, Menon BK, et al. Randomized assessment of rapid endovascular treatment of ischemic stroke. N Engl J Med 2015;372:1019-1030
3. Jovin TG, Chamorro A, Cobo E, et al. Thrombectomy within 8 hours after symptom onset in ischemic stroke. N Engl J Med 2015;372:2296-2306
4. Saver JL, Goyal M, Bonafe A, et al. Stent-retriever thrombectomy after intravenous t-PA vs. t-PA alone in stroke. N Engl J Med 2015;372:2285-2295
5. Campbell BC, Mitchell PJ, Kleinig TJ, et al. Endovascular therapy for ischemic stroke with perfusion-imaging selection. N Engl J Med 2015;372:1009-1018
6. Bracard S, Ducrocq X, Mas JL, et al. Mechanical thrombectomy after intravenous alteplase versus alteplase alone after stroke (THRACE): a randomised controlled trial. Lancet Neurol 2016;15:1138-1147
7. Nogueira RG, Jadhav AP, Haussen DC, et al. Thrombectomy 6 to 24 hours after stroke with a mismatch between deficit and infarct. N Engl J Med 2018;378:11-21
8. Albers GW, Marks MP, Kemp S, et al. Thrombectomy for stroke at 6 to 16 hours with selection by perfusion imaging. N Engl J Med 2018;378:708-718
9. Nael K, Sakai Y, Khatri P, Prestigiacomo CJ, Puig J, Vagal A. Imaging-based selection for endovascular treatment in stroke. Radiographics 2019;39:1696-1713

10. Lima FO, Furie KL, Silva GS, et al. The pattern of leptomeningeal collaterals on CT angiography is a strong predictor of long-term functional outcome in stroke patients with large vessel intracranial occlusion. Stroke 2010;41:2316-2322
11. Menon BK, d'Esterre CD, Qazi EM, et al. Multiphase CT angiography: a new tool for the imaging triage of patients with acute ischemic stroke. Radiology 2015;275:510-520
12. Hernández-Pérez M, Puig J, Blasco G, et al. Dynamic magnetic resonance angiography provides collateral circulation and hemodynamic information in acute ischemic stroke. Stroke 2016;47:531-534
13. Pfeifer CM. Rapid-sequence MRI of the brain: a distinct imaging study. AJNR Am J Neuroradiol 2018;39:E93-E94
14. Provost C, Soudant M, Legrand L, et al. Magnetic resonance imaging or computed tomography before treatment in acute ischemic stroke. Stroke 2019;50:659-664
15. Leslie-Mazwi TM, Hirsch JA, Falcone GJ, et al. Endovascular stroke treatment outcomes after patient selection based on magnetic resonance imaging and clinical criteria. JAMA Neurol 2016;73:43-49
16. Wisco D, Uchino K, Saqqur M, et al. Addition of hyperacute MRI AIDS in patient selection, decreasing the use of endovascular stroke therapy. Stroke 2014;45:467-472
17. Fink JN, Kumar S, Horkan C, et al. The stroke patient who woke up: clinical and radiological features, including diffusion and perfusion MRI. Stroke 2002;33:988-993
18. Mackey J, Kleindorfer D, Sucharew H, et al. Population-based study of wake-up strokes. Neurology 2011;76:1662-1667
19. Thomalla G, Simonsen CZ, Boutitie F, et al. MRI-guided thrombolysis for stroke with unknown time of onset. N Engl J Med 2018;379:611-622
20. Petkova M, Rodrigo S, Lamy C, et al. MR imaging helps predict time from symptom onset in patients with acute stroke: implications for patients with unknown onset time. Radiology 2010;257:782-792
21. Thomalla G, Cheng B, Ebinger M, et al. DWI-FLAIR mismatch for the identification of patients with acute ischaemic stroke within 4.5 h of symptom onset (PRE-FLAIR): a multicentre observational study. Lancet Neurol 2011;10:978-986
22. Logallo N, Novotny V, Assmus J, et al. Tenecteplase versus alteplase for management of acute ischaemic stroke (NOR-TEST): a phase 3, randomised, open-label, blinded endpoint trial. Lancet Neurol 2017;16:781-788
23. Vilela P, Rowley HA. Brain ischemia: CT and MRI techniques in acute ischemic stroke. Eur J Radiol 2017;96:162-172
24. Rowley H, Vagal A. Stroke and stroke mimics: diagnosis and Treatment. In Hodler J, Kubik-Huch RA, von Schulthess GK. eds. Diseases of the brain, head and neck, spine 2020-2023: Diagnostic Imaging. Cham (CH), 2020:25-36
25. Simonsen CZ, Yoo AJ, Rasmussen M, et al. Magnetic resonance imaging selection for endovascular stroke therapy: workflow in the GOLIATH trial. Stroke 2018;49:1402-1406
26. Poustchi-Amin M, Mirowitz SA, Brown JJ, McKinstry RC, Li T. Principles and applications of echo-planar imaging: a review for the general radiologist. Radiographics 2001;21:767-779
27. Chung MS, Lee JY, Jung SC, et al. Reliability of fast magnetic resonance imaging for acute ischemic stroke patients using a 1.5-T scanner. Eur Radiol 2019;29:2641-2650
28. Kozak BM, Jaimes C, Kirsch J, Gee MS. MRI techniques to decrease imaging times in children. Radiographics 2020;40:485-502
29. Deshmane A, Gulani V, Griswold MA, Seiberlich N. Parallel MR imaging. J Magn Reson Imaging 2012;36:55-72
30. Barth M, Breuer F, Koopmans PJ, Norris DG, Poser BA. Simultaneous multislice (SMS) imaging techniques. Magn Reson Med 2016;75:63-81
31. Feinberg DA, Setsompop K. Ultra-fast MRI of the human brain with simultaneous multi-slice imaging. J Magn Reson 2013;229:90-100
32. Vranic JE, Cross NM, Wang Y, Hippe DS, de Weerdt E, Mossa-Basha M. Compressed sensing-sensitivity encoding (CS-SENSE) accelerated brain imaging: reduced scan time without reduced image quality. AJNR Am J Neuroradiol 2019;40:92-98
33. Delattre BMA, Boudabbous S, Hansen C, Neroladaki A, Hachulla AL, Vargas MI. Compressed sensing MRI of different organs: ready for clinical daily practice? Eur Radiol 2020;30:308-319
34. Park SJ, Ahn CB. Blended-transfer learning for compressed-sensing cardiac cine MRI. Investig Magn Reson Imaging 2021;25:10-22
35. Willinek WA, Gieseke J, von Falkenhausen M, Neuen B, Schild HH, Kuhl CK. Sensitivity encoding for fast MR imaging of the brain in patients with stroke. Radiology 2003;228:669-675
36. U-King-Im JM, Trivedi RA, Graves MJ, et al. Utility of an ultrafast magnetic resonance imaging protocol in recent and semi-recent strokes. J Neurol Neurosurg Psychiatry 2005;76:1002-1005
37. Nael K, Khan R, Choudhary G, et al. Six-minute magnetic resonance imaging protocol for evaluation of acute ischemic stroke: pushing the boundaries. Stroke 2014;45:1985-1991
38. Prakkamakul S, Witzel T, Huang S, et al. Ultrafast brain

MRI: clinical deployment and comparison to conventional brain MRI at 3T. J Neuroimaging 2016;26:503-510
39. Ryu KH, Choi DS, Baek HJ, et al. Clinical feasibility of 1-min ultrafast brain MRI compared with routine brain MRI using synthetic MRI: a single center pilot study. J Neurol 2019;266:431-439
40. Skare S, Sprenger T, Norbeck O, et al. A 1-minute full brain MR exam using a multicontrast EPI sequence. Magn Reson Med 2018;79:3045-3054
41. Meshksar A, Villablanca JP, Khan R, Carmody R, Coull B, Nael K. Role of EPI-FLAIR in patients with acute stroke: a comparative analysis with FLAIR. AJNR Am J Neuroradiol 2014;35:878-883
42. Boujan T, Neuberger U, Pfaff J, et al. Value of contrast-enhanced MRA versus time-of-flight MRA in acute ischemic stroke MRI. AJNR Am J Neuroradiol 2018;39:1710-1716
43. Le Bras A, Raoult H, Ferre JC, Ronziere T, Gauvrit JY. Optimal MRI sequence for identifying occlusion location in acute stroke: which value of time-resolved contrast-enhanced MRA? AJNR Am J Neuroradiol 2015;36:1081-1088
44. Bak SH, Roh HG, Moon WJ, Choi JW, An HS. Appropriate minimal dose of gadobutrol for 3D time-resolved MRA of the supra-aortic arteries: comparison with conventional single-phase high-resolution 3D contrast-enhanced MRA. AJNR Am J Neuroradiol 2017;38:1383-1390
45. Chakhoyan A, Leu K, Pope WB, Cloughesy TF, Ellingson BM. Improved spatiotemporal resolution of dynamic susceptibility contrast perfusion MRI in brain tumors using simultaneous multi-slice echo-planar imaging. AJNR Am J Neuroradiol 2018;39:43-45
46. Glockner JF, Hu HH, Stanley DW, Angelos L, King K. Parallel MR imaging: a user's guide. Radiographics 2005;25:1279-1297
47. Riederer SJ, Haider CR, Borisch EA, Weavers PT, Young PM. Recent advances in 3D time-resolved contrast-enhanced MR angiography. J Magn Reson Imaging 2015;42:3-22
48. Giannatempo GM, Scarabino T, Popolizio T, Parracino T, Serricchio E, Simeone A. 3.0 T perfusion MRI dynamic susceptibility contrast and dynamic contrast-enhanced techniques. In Scarabino T, Pollice S, Popolizio T, eds. High field brain MRI. Springer, Cham, 2017:113-131
49. Shah S, Luby M, Poole K, et al. Screening with MRI for accurate and rapid stroke treatment: SMART. Neurology 2015;84:2438-2444