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Abstract

Background

Susceptibility-weighted imaging (SWI) is highly sensitive for intracranial hemorrhagic and mineralized lesions but is associated with long scan times. Wave controlled aliasing in parallel imaging (Wave-CAIPI) enables greater acceleration factors and might facilitate broader application of SWI, especially in motion-prone populations.

Objective

To compare highly accelerated Wave-CAIPI SWI to standard SWI in the non-sedated pediatric outpatient setting, with respect to the following variables: estimated scan time, image noise, artifacts, visualization of normal anatomy and visualization of pathology.

Materials and methods

Twenty-eight children (11 girls, 17 boys; mean age ± standard deviation [SD] = 128.3±62 months) underwent 3-tesla (T) brain MRI, including standard three-dimensional (3-D) SWI sequence followed by a highly accelerated Wave-CAIPI SWI sequence for each subject. We rated all studies using a predefined 5-point scale and used the Wilcoxon signed rank test to assess the difference for each variable between sequences.

Results

Wave-CAIPI SWI provided a 78% and 67% reduction in estimated scan time using the 32- and 20-channel coils, respectively, corresponding to estimated scan time reductions of 3.5 min and 3 min, respectively. All 28 children were imaged without anesthesia. Inter-reader agreement ranged from fair to substantial (k=0.67 for evaluation of pathology, 0.55 for anatomical contrast, 0.3 for central noise, and 0.71 for artifacts). Image noise was rated higher in the central brain with wave SWI ($P<0.01$), but not in the peripheral brain. There was no significant difference in the visualization of normal anatomical structures and visualization of pathology between the standard and wave SWI sequences ($P=0.77$ and $P=0.79$, respectively).

Conclusion

Highly accelerated Wave-CAIPI SWI of the brain can provide similar image quality to standard SWI, with estimated scan time reduction of 3–3.5 min depending on the radiofrequency coil used, with fewer motion artifacts, at a cost of mild but perceptibly increased noise in the central brain.

Keywords: Accelerated imaging, Brain, Children, Magnetic resonance imaging, Parallel imaging, Susceptibility-weighted imaging

Introduction

Magnetic resonance imaging (MRI) can depict susceptibility effects within tissues, hence the sensitivity to accumulation of blood products, mineralization and even small hemorrhages. The

susceptibility of a tissue indicates the degree of magnetization in response to an applied magnetic field. Susceptibility-weighted imaging (SWI) is a high-spatial-resolution three-dimensional (3-D) gradient echo MRI technique that accentuates the magnetic properties of various substances such as blood products, nonheme iron, calcifications, calcified neoplasms, vasculopathies and neurodegenerative disorders [1, 2]. It has been shown that SWI is 3–6 times more sensitive in detecting number, volume and distribution of hemorrhagic lesions in diffuse axonal injury than T2*-W two-dimensional gradient echo sequence (2-D GRE) [3]. A hindrance to routinely acquiring 3-D SWI sequences in brain MRI protocols is long scan times (typically 5 min or more), which result in greater motion artifacts and patient anxiety, particularly in young children.

Parallel imaging is a set of techniques that employs receiver sensitivity encoding to reconstruct images from under-sampled k-space acquisitions [4–8]. Wave-CAIPI is a recently developed data acquisition technique that enables parallel imaging at high acceleration factors with reduced g-factor (signal-to-noise ratio [SNR]) penalty. The "wave" in Wave-CAIPI refers to the oscillating gradient waveform that plays out in three dimensions during the readout. Instead of a standard readout gradient, where a single line of k-space is sampled, the wave readout gradients create a corkscrew (or wave-like) trajectory in k-space. This readout trajectory is designed to optimally spread the voxel aliasing (that results from under-sampling in parallel imaging) uniformly across all spatial dimensions, and this results in a lower SNR penalty for a given acceleration factor [6]. Like 2-D CAIPI, Wave-CAIPI chooses its phase-encoding positions to lie on a 2-D lattice in k-space for volumetric 3-D imaging, while the readout gradient is used to encode the third dimension. Periodic shifts of the readout trajectories in k-space help to reduce the resulting parallel imaging g-factor in an accelerated acquisition. However, distinct from 2-D CAIPI (in which the readout follows a straight-line path through k-space), Wave-CAIPI employs a 3-D corkscrew-shaped non-Cartesian readout trajectory. This scheme takes full advantage of the additional spatial encoding provided by 3-D coil sensitivity profiles and enables highly accelerated volumetric imaging with low artifact and negligible SNR penalties [7, 8]. This scan time reduction enables broader clinical application of SWI, especially in children, who are considered motion-prone populations.

The aim of this exploratory pilot study was to compare a highly accelerated SWI sequence based on Wave-CAIPI (wave SWI) to standard 3-D SWI in non-sedated pediatric

patients, with respect to the following variables: estimated scan time, image noise, presence of artifacts, visualization of anatomy and visualization of pathology.

Materials and methods

The human research committee of the institutional review board approved this prospective single-institutional study, which complied with the Health Insurance Portability and Accountability Act (HIPAA).

Patients

We prospectively enrolled 28 consecutive pediatric patients (11 girls, 17 boys; mean ± standard deviation [SD] age = 128.5±62 months) undergoing brain MRI examinations without anesthesia for clinically indicated reasons (Table 1). We only enrolled non-sedated children to have a higher chance of motion artifact. All guardians/parents gave written informed consent prior to the MRI scan. All children underwent clinical brain MRI on a 3-tesla (T) MRI system (Magnetom Prisma; Siemens Healthcare GmbH, Erlangen, Germany) from June 2018 to April 2019. The clinical indications were tumor (*n*=14), seizure (*n*=4), headache (*n*=4), evaluation of developmental delay (*n*=3), adrenoleukodystrophy (*n*=2) and suspected mitochondrial disorder (*n*=1). We explained the additional scan time to all parents prior to obtaining their written informed consent before the study. The inclusion criteria comprised hemodynamic stability, age ≤18 years, no sedation required, English-speaking parents. We excluded children with ventriculoperitoneal shunt or medical implants and those who were undergoing urgent MRI.

Magnetic resonance imaging protocol and processing

All children underwent brain MRI on a 3-T MRI scanner (Siemens Healthcare) using 20- and 32-channel receiver coil arrays. A prototype dual-echo 3-D gradient echo pulse sequence was used to implement wave SWI [9]. Image reconstruction was performed in approximately 60 s, with an auto-calibrated procedure for simultaneous estimation of the parallel imaging reconstruction and true k-space trajectory (i.e. accounting for imperfect implementation of the corkscrew readout trajectory to non-idealities in the imaging gradients) [10]. Standard institutional brain MRI protocols were selected by the radiologist based on the provided clinical indication. Each scan

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included the standard SWI and a highly accelerated wave SWI sequence performed immediately after the conventional sequence. A summary of the scan parameters is shown in Table 2.

Semiquantitative evaluation

All brain MR image datasets were anonymized and reviewed on a picture archiving and communication system (PACS) diagnostic workstation (AGFA Impax ES; AGFA Technical Imaging Systems, Mortsel, Belgium) by two independent pediatric neuroradiologists (M.G.F.L. and J.C. with 9 and 10 years of experience, respectively), blinded to patient information and protocol type. To obtain optimal visualization, adjustments of window widths and levels were allowed. Only the SWI sequences were evaluated in each session.

The images acquired using the wave SWI and standard SWI were presented head-to-head. The left/right screen position of the wave SWI and standard SWI images were presented in random order, so that the same sequence would not always appear on the same side of the screen. The raters compared and scored the two sequences for each of the following variables: visualization of pathology, subjective perception of noise (central and peripheral), visualization of normal anatomical structures (vessels and basal ganglia, selected for their intrinsic susceptibility contrast) and presence of artifacts (including motion, signal dropout — i.e. signal voids that can occur at the interface between tissues with different magnetic susceptibility, and parallel imaging artifacts). Noise was separately evaluated in the central brain (deep gray nuclei, brainstem and thalami) and peripheral brain (cortex, and subcortical and deep white matter) to evaluate for spatial variation in perceived image noise that can occur from intrinsic coil sensitivity or parallel imaging (i.e. spatially varying g-factor) [6]. The two readers used a predefined 5-point scale, where positive numbers favored the sequence on the right and negative numbers favored the sequence on the left of the screen (Table 3) [11]. A third neuroradiologist (P.J.C. with 21 years of experience), adjudicated the disagreements between readers.

Statistical analysis

We reported inter-rater agreement using the weighted Cohen κ coefficient according to the standard interpretation of Landis and Koch [12]. The ordinal radiologist scores were compared between wave SWI and standard SWI using the Wilcoxon signed rank test. To evaluate the impact of coil selection on SNR, we compared the proportion of cases where image noise was

greater for wave SWI than standard SWI between the 32-channel and 20-channel head coils using the Fisher exact test. All statistical calculations were performed using R version 3.4.3. [12–14]. A *P*-value <0.05 was regarded as significant.

Results

Wave SWI data were successfully acquired and images successfully reconstructed in 100% (28/28) of the cases. Wave-CAIPI SWI provided a 78% reduction in estimated scan time using the 32-channel coil (*n*=15; estimated acquisition time = 1 min vs. 4 min 30 s for standard SWI) and a 67% reduction using the 20-channel coil (*n*=13; estimated acquisition time = 1 min 30 s vs. 4 min 30 s for standard SWI). Wave-CAIPI SWI was performed following standard SWI sequence and evaluated in all 28 children (total of 56 images). We compared abnormalities between the two sequences. Inter-reader agreement ranged from fair to substantial: κ=0.67, 95% confidence interval (CI) = 0.38–0.96, for evaluation of pathology; κ=0.55, 95% CI 0.17–0.93, for evaluation of anatomical contrast; κ=0.3, 95% CI 0.01–0.54, for evaluation of central noise; and κ=0.71, 95% CI 0.33–1.0, for evaluation of artifacts. For peripheral noise, Cohen κ was negative (κ=–0.14 (95% CI –0.24 to –0.05) despite a high proportion of agreement, wherein both raters agreed on a score of 0 in the majority of cases (Table 4). This known paradoxical result can occur when the study population is highly unbalanced [15] (in this study, there was a much higher proportion of 0 vs. non-0 scores). Visualization of normal anatomical structures and evaluation of pathology including hemorrhage and mineralization were not significantly different between the standard and wave SWI (*P*=0.77 and *P*=0.79, respectively) (Fig. 1).

Image noise was rated higher in the central brain with wave SWI (*P*<0.01), but not in the peripheral brain, likely because of the intrinsic SNR profile of the head coil, which has greater signal in the peripheral brain near the receiver coil elements (Fig. 2), as well as the g-factor profile of Wave-CAIPI acceleration, which is higher (though still typically small) in the central than the peripheral brain [6]. There were no cases (0/28) where this difference impacted the final diagnosis (i.e. there were no scores of +2 or –2 in the evaluation of image noise). The results of the head-to-head comparison are shown in Fig. 3. When comparing the two head coils with respect to image noise, central noise was greater on the wave SWI sequence than the standard SWI sequence in 9/15 cases using the 32-channel coil and 4/13 cases using the 20-channel coil

(*P*=0.15, no significant difference between coils). The adjudicated peripheral noise scores were rated as equal between wave SWI and standard SWI in all cases.

Representative images illustrating the comparison between standard SWI and wave SWI for each of the variables evaluated are provided in Fig. 4.

Discussion

Our results show that an accelerated wave SWI pulse sequence can decrease estimated scan time by 67–78% compared to standard SWI (3.5-min estimated scan time reduction on a 32-channel coil, 3-min estimated scan time reduction on a 20-channel coil). This compares similarly with previous studies applying highly accelerated SWI sequence in adult brain MR imaging [16, 17]. For pediatric MRI, reductions in both acquisition time and exposure to general anesthesia continue to be strategic goals for the clinical community [18, 19].

Specific to pediatrics, the SWI sequence is often employed in pediatric "quick brain MRI" studies (in combination with triplanar T2-weighted half-Fourier acquisition single-shot turbo spin-echo [HASTE] images and diffusion-weighted images) to evaluate for intracranial hemorrhage in the setting of head trauma [20]. The use of Wave-CAIPI to reduce the estimated scan time of SWI acquisitions might facilitate the deployment of SWI as an added contrast to pediatric "quick brain MRI" protocols for trauma and other applications such as seizure and stroke workup [21], where SWI is helpful for the exclusion of hemorrhage. Prior work evaluating a 5-min whole-brain protocol [22] used a 2-D gradient echo sequence as a "hemorrhage-sensitive" sequence; this sequence is usually chosen in fast MRI protocols because of its shorter estimated scan time. However, 3-D susceptibility-weighted imaging sequences (including the wave SWI sequence evaluated here) are substantially more sensitive for small hemorrhages than 2-D gradient echo sequences, which has been convincingly demonstrated in the literature [23]. Thus, the choice of 2-D GRE sequences over 3-D SWI sequences has historically been made to decrease the overall estimated scan time of a protocol. While one previous study evaluated the Wave-CAIPI 3-D imaging approach for T1-weighted magnetization-prepared rapid gradient echo imaging (MP-RAGE) in non-sedated children [24], to our knowledge ours is the first study to evaluate Wave-CAIPI SWI in a pediatric population.

The shorter estimated scan time can result in reduced patient anxiety and potentially reduced need for sedation; in the future, application of wave sequences for sedated children could reduce the duration of sedation and any associated adverse effects such as hypoxia and long-term effects of general anesthesia on cognitive development [25–27]. Moreover, a sedated MRI examination utilizes considerably higher resources such as time, cost and trained personnel compared with non-sedated MRI examination [28]. These considerations have resulted in identifying MRI scanning techniques that are rapid enough to permit awake free-breathing scanning while reducing motion artifacts.

In addition to decreasing acquisition time, the fast sequences showed fewer motion-related artifacts, an additional benefit in pediatric populations. The subjective evaluation of image quality in the head-to-head analysis demonstrated no difference in visualization of pathology and normal anatomical structures, and superiority for motion artifacts, with reduced estimated scan time (scan time reduction of 3.5 min on the 32-channel coil and 3 min on the 20-channel coil) in wave SWI when compared to standard SWI. More severe artifact was observed in standard SWI images in five cases (18%) when compared to wave SWI, likely as a direct consequence of the longer acquisition time making it more difficult for the child to remain still for the full duration of the scan. When comparing images obtained using 32-channel and 20-channel receiver coils, one might expect a difference in image noise, with less visible noise on the 32-channel coil. However, we chose to trade the additional SNR provided by the 32-channel coil for greater acceleration by using a higher acceleration factor (R=9 on the 32-channel coil, R=6 on the 20-channel coil; Table 2), such that the SNR of the resulting images was similar.

Our study has some limitations. First, we used a small sample size of children that primarily included older children who might be better able to hold still, and as such our results should be considered as preliminary and exploratory. Nevertheless, this pilot study outlines the potential of the accelerated SWI technique to reduce estimated scan time in clinical imaging protocols, particularly if it can ultimately be extended across multiple contrasts, an important area for future research. Further, given the small number of very young children (n=5 younger than 5 years) and small number of children with developmental delay (n=2), further evaluation of wave SWI in dedicated studies of these highly motion-prone populations would be helpful to determine whether they would benefit to an even greater degree from reduced motion artifacts with the accelerated wave SWI sequence. Second, not all children in this cohort had pathology

on the SWI sequence. Future study incorporating larger numbers of children with specific pathologies is required before adopting wave SWI for targeted clinical applications (e.g., traumatic brain injury, neuro-oncology, neonatal encephalopathy). Furthermore, diagnostic accuracy was not the scope of this study; instead, we sought to evaluate the clinical robustness of the sequence and potential for reducing protocol duration if it can be ultimately adopted into the clinical routine practice. Third, we used a slice thickness of 1.8 mm because this was rigorously evaluated in a previous study of an adult population [16]. Although our default pediatric protocol used a slice thickness of 1.5 mm, the prototype wave SWI sequence was still under development by the vendor, so we did not want to stray beyond the range of parameter settings that had been previously tested in other studies; relatively small changes in parameter settings that affect the geometry of the acquisition could in theory affect factors such as the parallel imaging performance, and decreasing the slice thickness would also be associated with an increase in estimated scan time and SNR penalty from thinner slices. As the technology evolves and undergoes further validation by the vendor under a wider range of parameter settings, more precise parameter matching in future studies should be possible. Fourth, only a 3-T MR scanner was used in this study; therefore, the image quality at other field strengths (1.5 T and 7 T) remains unknown. Evaluation at 1.5 T, in particular, is needed to extend the clinical utility and impact of the technique because a majority of clinical MRI is performed on 1.5-T scanners.

Conclusion

Wave SWI of the brain can provide similar image quality to standard SWI, with estimated scan time reduction of 3 min to 3.5 min, depending on the radiofrequency coil used, and fewer motion artifacts. This comes at a cost of mild but perceptibly increased noise in the central brain. Further clinical validation studies to determine the diagnostic accuracy of wave SWI in specific clinical scenarios (e.g., neuro-oncology, traumatic brain injury and neonatal encephalopathy) are warranted.

Acknowledgments

John Conklin and Azadeh Tabari contributed equally to this publication.

Declarations

Conflicts of interest

None

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Fig. 1 Representative axial images comparing standard and wave susceptibility-weighted imaging (SWI). **a–d** Standard SWI (**a, c**) and wave SWI (**b, d**). Images (**a**) and (**b**) illustrate comparative image quality in the visualization of normal anatomical structures (the basal ganglia and vessels) in a 12-year-old boy using the 32-channel coil. Images (**c**) and (**d**) illustrate low-grade astrocytoma in an 11-year-old boy using the 20-channel coil. Both SWI sequences show an area of hemorrhage (curvilinear hypointense signal) in the right basal ganglia, compatible with intralesional hemorrhage in the treated tumor. Visualization of the normal anatomical structures and the pathology was rated as equivalent (score of 0) between standard and wave SWI sequences in these cases by both interpreting radiologists

Fig. 2 Standard vs. wave susceptibility-weighted imaging (SWI) in a 13-year-old girl with nonspecific focus of susceptibility signal in the left temporal lobe. **a, b** Representative axial images compare (**a**) standard SWI and (**b**) wave SWI using the 20-channel coil. The focus of susceptibility was equally well observed on both SWI sequences, compatible with a microhemorrhage or small cavernous malformation (*arrow*). Noise is more visible with wave SWI in the central brain (*box*) compared to peripheral brain, likely because of the intrinsic signal-to-noise profile of the head coil, which has greater signal in the peripheral brain near the receiver coil elements

Fig. 3 Balloon plot shows the results of the head-to-head comparison of standard susceptibility-weighted imaging (SWI) and wave controlled aliasing in parallel imaging (wave-CAIPI), or wave SWI. The size of each circle represents the percentage of cases that were assigned a given score, from a total of 28 abnormal cases. Negative scores (*left*) favor standard SWI, and positive scores (*right*) favor wave SWI. The *P*-values for wave SWI compared to standard SWI were calculated using Wilcoxon signed rank test. While the standard SWI cases demonstrate more central noise ($P<0.01$), the overall presence of artifact was decreased on the wave SWI sequence ($P=0.03$), attributable to fewer motion artifacts on the faster wave SWI acquisition. $P<0.05$ is significant

Fig. 4 Representative axial images comparing standard susceptibility-weighted imaging (SWI) (first and third columns) and wave SWI (second and fourth columns) in terms of the different image-quality metrics. **a-d** First row, visualization of normal anatomical structures. **a,b** Axial images in a 13-year-old girl undergoing surveillance MRI using a 20-channel coil for remotely treated medulloblastoma show visualization of normal vessels (*arrow*) and basal ganglia (*arrowhead*). Standard SWI (**a**) was preferred as compared to wave SWI (**b**) (the score of 1 favored standard SWI). **c,d** Axial images in 12-year-old boy undergoing surveillance MRI using 32-channel coil for x-linked adrenoleukodystrophy show visualization of normal vessels (*arrow*) and basal ganglia (*arrowhead*). In this set, the wave SWI (**c**) was preferred compared to standard SWI (**d**) (score of 1 favoring wave SWI). **e-h** Second row, perception of noise. **e,f** Axial standard SWI (**e**) and wave SWI (**f**) in a 35-day-old girl undergoing MRI using 32-channel coil for evaluation of seizures. In the central brain (*box*), noise was more visible on wave SWI (**f**) compared to standard SWI (**e**) (score of 1 favored standard SWI). **g,h** In the peripheral brain, noise was rated equal between the two sequences (score of 0). In a 16-year-old boy undergoing

MRI using 32-channel coil for evaluation of epilepsy, noise was rated equal between the two sequences (standard, **g**; wave, **h**) for both the central and peripheral brain (scores of 0 for both central and peripheral noise). **i-l** Third row, presence of artifacts. **i.j** In an 11-year-old boy with decreased height velocity and concern for pediatric endocrinopathy undergoing MRI using the 20-channel coil, motion artifact is present on both sequences (*arrows*), and was considered equal in severity (score of 0) on the standard SWI (**i**) and wave SWI (**j**) images. **k,l** In an 8-year-old boy undergoing surveillance MRI on 20-channel coil for x-linked adrenoleukodystrophy, severe motion artifact is present on standard SWI (**k**), rendering the images non-diagnostic. Milder motion artifact is present on wave SWI (**l**), but some normal anatomical features are still visible (score of 2 favored wave SWI). **m-p** Fourth row, visualization of pathology. **m,n** Standard (**m**) and wave (**n**) SWI sequences in a 12-year-old girl with a history of craniopharyngioma and resection of a cystic lesion centered in the left inferior frontal lobe, undergoing brain MRI using the 20-channel coil. Hemosiderin staining along the margins of the left frontal lobe resection cavity (*arrows*) is equally visible on wave SWI and standard SWI (score of 0). **o,p** In a 9-year-old boy undergoing surveillance MRI on the 20-channel coil for right temporal lobe anaplastic glioma, status post resection and chemoradiation, axial SWI sequences show punctate foci of susceptibility signal in the right temporal lobe and right midbrain (*arrows*), likely related to prior radiation treatment. The pathology is visible on both sequences, but the raters thought the lesions were better visualized on standard SWI (**o**) compared to wave SWI (**p**) (score of 1 favored standard SWI)

Table 1 Patient demographics and clinical characterization

	Wave-SWI** and Standard-SWI
Number of children	28
Age (Months)	128.5 ± 62
n ≤ 60	5
60 < n ≤ 120	5
n > 120	18

Clinical Indication for MRI (n)

Tumor	14
Seizure	4
Headache	4
Developmental delay	3
ALD*	2
Suspected mitochondrial disorder	1

*ALD, adrenoleukodystrophy

**Wave-SWI acquired after standard sequence in all patients

Table 2 Acquisition Parameters for Susceptibility-Weighted Imaging Sequences

Parameter		Standard SWI	Wave-SWI
FOV read (mm)		230 x 208	240
FOV phase (%)		75.0	87.5
Matrix		256 x 220	288 x 189
Slice thickness (mm)		1.5	1.8
TR/TE (msec)		26/19.2	40/(13 and 30; effective TE 21.5)
Flip angle (degree)		15	15
Acceleration factor R	20-ch	GRAPPA, R=2	Wave-CAIPI, R=6
	32-ch	GRAPPA, R=2	Wave-CAIPI, R=9
Bandwidth (Hz/pixel)		120	100
Estimated scan time	20-ch	4min 30s	1min 30s

(sec)   32-ch   4min 30s   1min

SWI susceptibility-weighted imaging, *FOV* field of view, *GRAPPA* generalized autocalibrating partial parallel acquisition, *CAIPI* controlled aliasing in parallel imaging

Table 3 Semiquantitative Scoring Criteria Used for Head-to-Head comparison of Wave-SWI vs. Standard SWI

	Favors Image in the LEFT*			Favors Image in the RIGHT*	
Parameter	Score -2	Score -1	0	Score +1	Score +2
Visualization of Pathology	Visualization of pathology is superior on Image LEFT; lesions are not visualized on Image RIGHT	Visualization of pathology is preferred on Image LEFT, but lesions are still visualized on Image RIGHT	Equivalent	Visualization of pathology is preferred on Image RIGHT, but lesions are still visualized on Image LEFT	Visualization of pathology is superior on Image RIGHT; lesions are not visualized on Image LEFT
Noise (central and peripheral)	Image RIGHT has more subjectively perception of noise that may obscure small lesions	Image RIGHT has more subjectively perception of noise but small lesions are not obscured	Equivalent	Image LEFT has more subjectively perception of noise but small lesions are not obscured	Image LEFT has more subjectively perception of noise that may obscure small lesions

Artifacts	Image RIGHT has more artifacts that may obscure small lesions	Image RIGHT has more artifacts, but small lesions are not obscured	Equivalent	Image LEFT has more artifacts, but small lesions are not obscured	Image LEFT has more artifacts that may obscure small lesions
Anatomy Evaluation (vessels and basal ganglia)	N/A	The anatomic structures are better visualized on Image LEFT	Equivalent	The anatomic structures are better visualized on Image RIGHT	N/A

* The Wave-SWI and standard susceptibility sequences were randomly positioned on either the right or left side of the screen. SWI, susceptibility-weighted imaging; N/A, not applicable

Table 4 The inter-reader agreement for subjective image assessment

Cohen's k [95% CI]

Pathology	0.67 [0.38, 0.96]
Anatomic contrast	0.55 [0.17, 0.93]
Central noise	0.3 [0.01, 0.54]
Peripheral noise	-0.14 [-0.24, -0.05]*
Artifacts	0.71 [0.33, 1.0]

* For peripheral noise, Cohen k was negative despite a high proportion of agreement, a known paradoxical result that can occur [15] and is discussed in the Results section