

# Ultrafast Multi-Contrast High-Resolution 3D Brain MRI: Clinical Evaluation of Wave-CAIPI Acceleration in SWI, MPRAGE, FLAIR, SPACE

Augusto Lio Goncalves Filho<sup>1</sup>; John Conklin<sup>1,2</sup>; Otto Rapalino<sup>3</sup>; Pamela Schaefer<sup>3</sup>; Susie Huang<sup>1,3</sup>

<sup>1</sup>Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Charlestown, MA, USA

<sup>2</sup>Division of Emergency Radiology, Department of Radiology, Massachusetts General Hospital, Boston, MA, USA

<sup>3</sup>Division of Neuroradiology, Department of Radiology, Massachusetts General Hospital, Boston, MA, USA

Magnetic Resonance Imaging (MRI) stands out among today's many medical imaging techniques as the best modality for studying the human brain. High field MRI scanners have improved many forms of structural and functional imaging by reducing voxel sizes and providing significant gains in signal-to-noise ratio (SNR) with an increase in image resolution [1]. Technological developments have also enabled more widespread use of 3D imaging sequences that allow for multiplanar image reconstruction with detailed anatomic depiction and high sensitivity in lesion detection. Traditionally, achieving high-resolution imaging has demanded long encoding and acquisition times that resulted in a lengthy total protocol.

With an eye toward limited scanner resources and the ever-growing demand for medical imaging, efforts have been made to reduce the duration of MRI acquisitions. Parallel imaging techniques such as generalized autocalibrating partially parallel acquisition (GRAPPA) and sensitivity encoding (SENSE) acquisitions have been successfully used to accelerate MRI acquisitions by two- to threefold in clinical practice by taking advantage of the inherent spatial encoding information of modern multichannel receiver arrays [1, 2]. Nevertheless, extreme accelerations have not been possible due to limitations in SNR imposed by higher *g*-factor penalties and aliasing artifacts. The Wave-CAIPI<sup>1</sup> method has recently been proposed as a

**Table 1:** Representative acquisition times of standard and accelerated 3D sequences performed on a 3T MAGNETOM scanner with 20-channel and 32-channel coil arrays. R = acceleration factor.

Sequence	Acquisition Time		
	Standard (GRAPPA)	3D Wave-CAIPI 20-ch coil	3D Wave-CAIPI 32-ch coil
SWI	5 min 21 s (R = 2)	1 min 37 s (R = 6)	1 min 6 s (R = 9)
MPRAGE	5 min 18 s (R = 2)	1 min 46 s (R = 6)	1 min 11 s (R = 9)
SPACE FLAIR	7 min 15 s (R = 2)	2 min 45 s (R = 6)	1 min 50 s (R = 9)
Post-contrast T1 SPACE	4 min 19 s (R = 4)	1 min 40 s (R = 9)	1 min 40 s (R = 9)

<sup>1</sup>Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.

way to enable greater acceleration of high-resolution volumetric imaging by combining *k*-space undersampling of CAIPIRINHA with corkscrew readout gradient trajectories that optimally utilize the intrinsic spatial information of the coil array, enabling increased acquisition speed with reduced noise amplification and artifact [2]. Wave-CAIPI is specifically designed to accelerate 3D exams, which offer the potential for increased diagnostic information by avoiding thick imaging slices and slice gaps, while providing multiplanar views and eliminating the need for redundant acquisitions in different planes. With support of Siemens Healthineers MR, this article will demonstrate the clinical experience and translational studies being performed at Massachusetts General Hospital (MGH) to validate the use of Wave-CAIPI acquisitions in a high-volume tertiary care setting with satellite outpatient facilities serving the large, diverse population of the greater Boston area.

The development, optimization and translation of Wave-CAIPI technology has been carried out by a multi-disciplinary team of MR physicists, Siemens Healthineers engineers, and neuroradiologists at MGH. Following the optimization of sequence parameters and online reconstruction using an autocalibrated procedure [3], we have sought to evaluate systematically the diagnostic performance of 3D Wave-CAIPI sequences against standard clinical protocols acquired with conventional parallel imaging (GRAPPA). The validation approach comprises prospective comparative studies including inpatient and outpatient examinations with a variety of indications and undergoing different imaging protocols that include SWI, MPRAGE, SPACE FLAIR and post-contrast T1 SPACE sequences. Imaging was performed on 3T

MAGNETOM Skyra and MAGNETOM Prisma MRI scanners (Siemens Healthcare, Erlangen, Germany) using Siemens 20- and 32-channel head coils. Acceleration factors were tailored for each pulse sequence and RF coil to balance scan time (Table 1) with an acceptable SNR for each coil configuration.

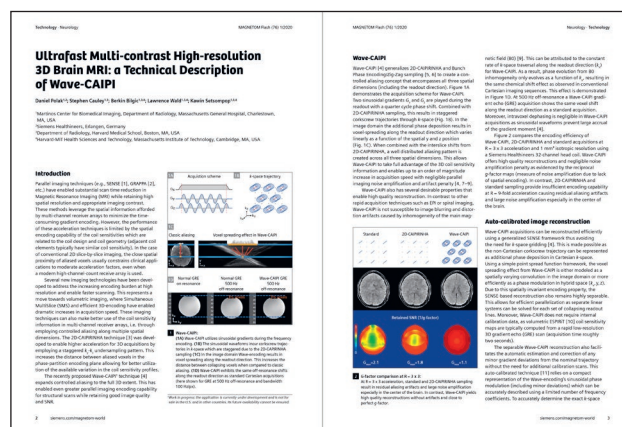
The approach to optimize and clinically validate diagnostic protocols incorporating Wave-CAIPI technology included the following steps:

1. Optimization of acquisition parameters for each sequence, including optimization of the Wave corkscrew to reduce noise amplification and blurring artifacts.
2. Establishing the ideal balance between maximum acceleration and adequate visualization of abnormal findings without loss of diagnostic capability compared to the standard exam.
3. Execution of an Institutional Review Board approved study to assess the head-to-head performance of the rapid MR protocol to the conventional exam with blinded reads by at least two board-certified neuroradiologists. The imaging evaluation incorporates a semiquantitative grading system to compare predetermined criteria on the Wave-CAIPI sequences with the standard sequence, including factors such as image quality, presence of artifacts, and diagnostic findings appropriate for the indication. The statistical demonstration of noninferiority of the Wave-CAIPI sequence compared to the standard sequence was used to validate the clinical utility of the accelerated imaging sequence, with an emphasis on preserving diagnostic performance.

## → Don't miss the technical description of Wave-CAIPI in the article by Kawin Setsompop, et al.

### "Ultrafast Multi-contrast High-resolution 3D Brain MRI: a Technical Description of Wave-CAIPI"

The article is available at  
[www.siemens.com/magnetom-world](http://www.siemens.com/magnetom-world)  
 > Clinical Corner > Case Studies



## Clinical experience with Wave-CAIPI sequences:

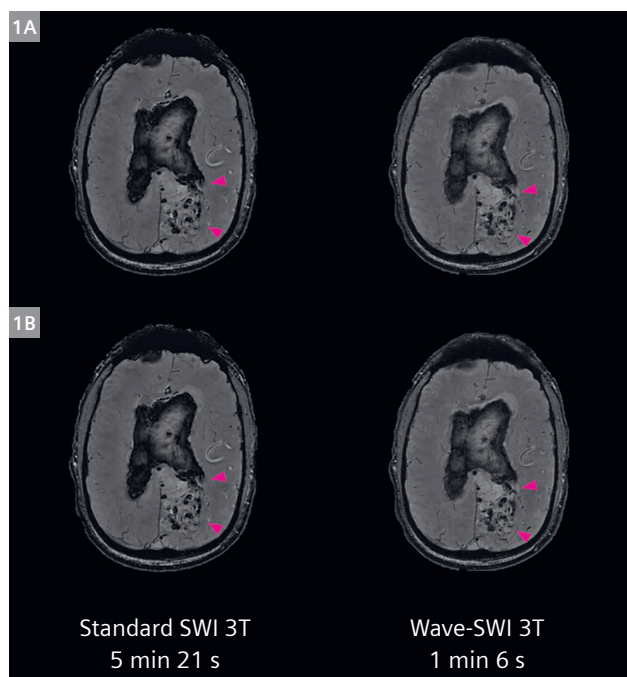
### Wave-SWI<sup>1</sup>

Wave-CAIPI SWI has been validated for routine clinical brain imaging at 3T and 1.5T. The results of a recent study have shown that Wave-SWI provided superior visualization of pathology and overall diagnostic quality compared with T2\*-weighted GRE and was noninferior to standard SWI with reduced scan time (Table 2) and reduced motion artifacts [4] (Fig. 1).

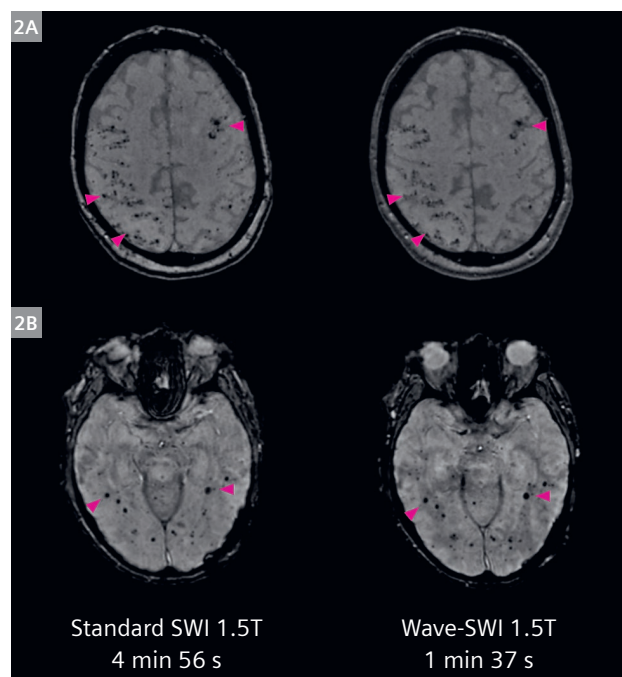
Given the predominance of 1.5T scanners in clinical practice, we have also conducted a smaller scale clinical study of Wave-SWI at 1.5T. The results of this study show comparable diagnostic performance of Wave-SWI to standard SWI at 1.5T (Fig. 2), thereby supporting the broad clinical adoption of Wave-SWI at both 1.5T and 3T.

**Table 2:** Representative acquisition parameters of standard and accelerated 3D SWI sequences performed on a 3T MAGNETOM scanner with 20-channel and 32-channel coil arrays.

	FOV read (mm)	FOV phase (%)	Matrix size	Slice thickness (mm)	TR/TE (msec)	Flip angle (degree)	Acceleration factor <i>R</i>		Scan time	
							20-ch	32-ch	20-ch	32-ch
Standard SWI	240	75.0	256 x 182	1.8	30/20	12	GRAPPA, <i>R</i> = 2	GRAPPA, <i>R</i> = 2	4 min 56 s	5 min 21 s
Wave-SWI	240	87.5	288 x 189	1.8	40/ (13 and 30; effective TE 21.5)	15	Wave-CAIPI, <i>R</i> = 6	Wave-CAIPI, <i>R</i> = 9	1 min 37 s	1 min 6 s



**1** Representative images comparing standard susceptibility-weighted imaging (Standard SWI) and Wave-CAIPI SWI (Wave-SWI) at 3T with a 32-channel coil array. **(1A)** Extensive intraventricular hemorrhage and serpiginous foci of susceptibility effect corresponding to an arteriovenous malformation. **(1B)** Focal subarachnoid hemorrhage in the left superior frontal sulcus and the pre-central sulcus.



**2** Representative images comparing standard susceptibility-weighted imaging (Standard SWI) and Wave-CAIPI SWI (Wave-SWI) at 1.5T with a 20-channel coil array. **(2A)** Cortical and juxtacortical punctate susceptibility foci due to amyloid angiopathy. **(2B)** Multiple small hemangioblastomas within the temporal and occipital lobes in a 57-year-old man with von Hippel Lindau syndrome.

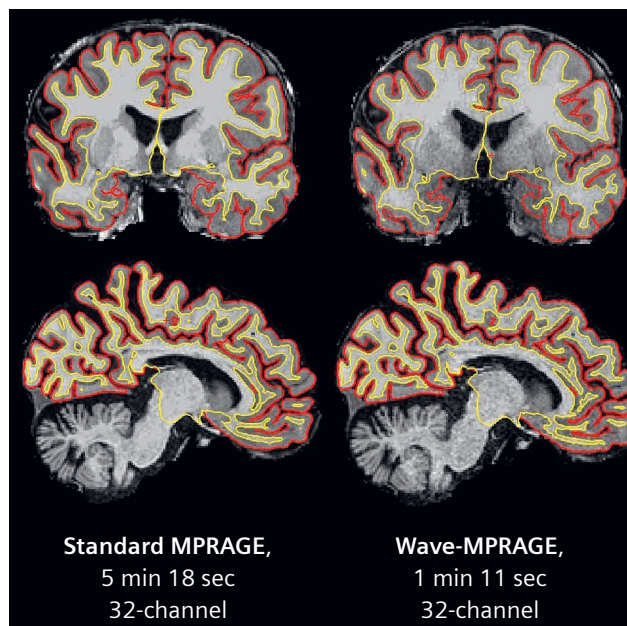
### Wave-MPRAGE<sup>1</sup>

Wave-CAIPI has been optimized for brain imaging with MPRAGE and has demonstrated potential in accelerating the evaluation of cortical volume in healthy volunteers [6]. In a recent study, Wave-MPRAGE<sup>1</sup> was evaluated in a clinical setting among patients undergoing evaluation for suspected neurodegenerative disease. The results revealed similar reliability to standard MPRAGE for regional evaluation of brain atrophy using automated segmentation of

brain tissue volumes, cortical thickness measurements, and semi-quantitative visual rating scales, despite a 3- to 5-fold decrease in acquisition time [7] (Table 3, Fig. 3). Therefore, adoption of Wave-MPRAGE over standard MPRAGE for volumetric imaging of patients with suspected neurodegenerative diseases could improve utilization of MRI resources in both clinical and research settings.

**Table 3:** Representative acquisition parameters of standard and accelerated 3D MPRAGE sequences performed on a 3T MAGNETOM scanner with 20-channel and 32-channel coil arrays.

	FOV read (mm)	FOV phase (%)	Matrix size	Slice thickness (mm)	TR/TE/TI (msec)	Flip angle (degree)	Acceleration factor <i>R</i>		Scan time	
							20-ch	32-ch	20-ch	32-ch
Standard MPRAGE	240 x 240	100	256 x 256	0.89	2300 / 2.32 / 900	8	GRAPPA, <i>R</i> = 2	GRAPPA, <i>R</i> = 2	5 min 19 s	5 min 18 s
Wave-MPRAGE	256 x 256	100	256 x 256	1.0	2500 / 3.48 / 1100	7	Wave-CAIPI, 3 x 2	Wave-CAIPI, 3 x 3	1 min 46 s	1 min 11 s



**3** Comparison of Wave-MPRAGE images in a patient with biparietal atrophy. Cortical volumes were generated by the FreeSurfer longitudinal processing stream. The lines represent the automated FreeSurfer outputs for the pial surface (red) and gray-white matter surface (yellow). These outputs demonstrate the accuracy of the longitudinal stream in both Wave-MPRAGE and standard MPRAGE images.

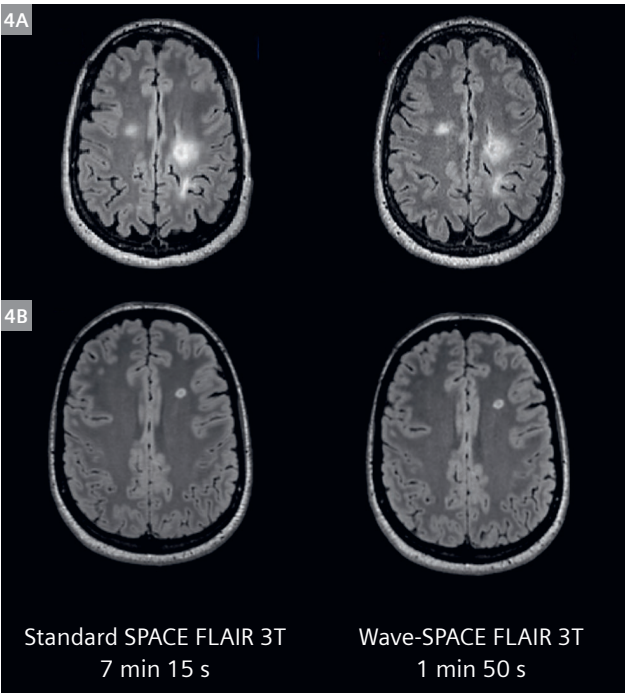
Wave-SPACE FLAIR<sup>1</sup>

Quantitative and qualitative evaluation of cerebral white matter lesions in a clinical setting has been explored using different flip angle evolution (SPACE) FLAIR sequences with Wave-CAIPI encoding (Wave-SPACE FLAIR) in comparison to standard SPACE FLAIR [7]. Preliminary results show excellent agreement in lesion detection between Wave-CAIPI and standard SPACE-FLAIR in patients undergoing clinical

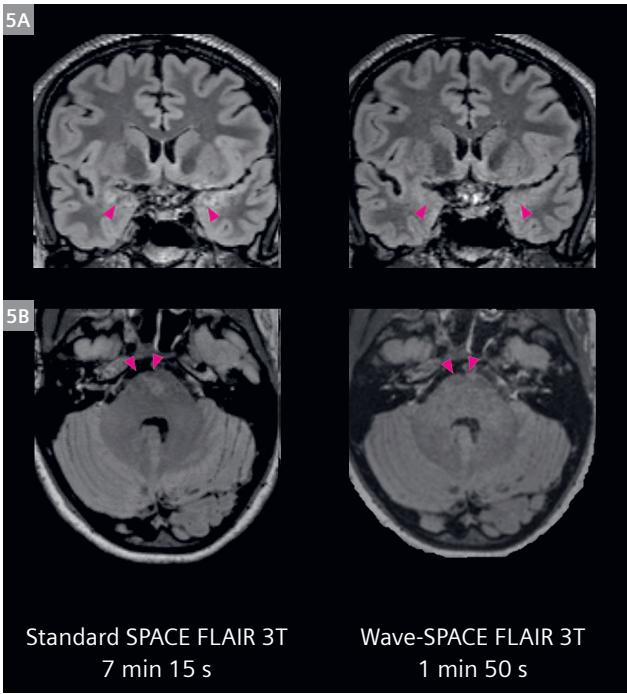
evaluation for multiple sclerosis (MS) and epilepsy, in less than half the acquisition time (Table 4, Fig. 4). Additionally, Wave-CAIPI SPACE FLAIR eliminates flow artifacts in the posterior fossa and middle cranial fossa that are commonly seen in the standard SPACE-FLAIR sequence (Fig. 5) which can confound the detection of subtle lesions in both MS and epilepsy.

**Table 4:** Representative acquisition parameters of standard and accelerated 3D SPACE FLAIR sequences performed on a 3T MAGNETOM scanner with 20-channel and 32-channel coil arrays.

	FOV read (mm)	FOV phase (%)	Matrix size	Slice thickness (mm)	TR/TE/TI (msec)	Flip angle (degree)	Acceleration factor <i>R</i>		Scan time	
							20-ch	32-ch	20-ch	32-ch
Standard SPACE FLAIR	256	100	256 x 256	1	5000/ 390/ 1800	120	GRAPPA, <i>R</i> = 2	GRAPPA, <i>R</i> = 2	7 min 15 s	7 min 15 s
Wave-SPACE FLAIR	256 x 256	100	256 x 256	1	5000/ 392/ 1800	120	Wave-CAIPI, <i>R</i> = 6	Wave-CAIPI, <i>R</i> = 9	2 min 45 s	1 min 50 s



**4** White matter lesions in (4A) multiple sclerosis and (4B) suspected multiple sclerosis on Standard SPACE FLAIR and Wave-SPACE FLAIR at 3T with a 32-channel coil.



**5** Representative images showing flow artifacts in the (5A) mesial temporal lobes and (5B) posterior fossa on the standard SPACE-FLAIR images that are not seen on the Wave-SPACE FLAIR images. In (5B), a pseudolesion in the central pons related to flow artifact around is not seen on the Wave-SPACE FLAIR image. Images were acquired at 3T on a 32-channel coil.



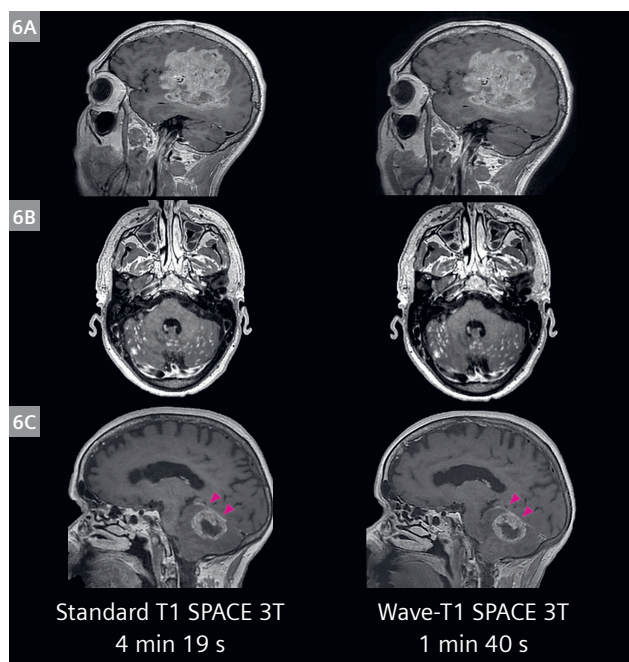
### Wave-T1 SPACE<sup>1</sup>

Evaluation of diagnostic performance and image quality of highly accelerated Wave-CAIPI post-contrast 3D-T1 SPACE (Wave-T1 SPACE) compared to standard post-contrast 3D-T1 SPACE has also been performed for the detection of intracranial enhancing lesions [8]. There was no significant difference in the visualization of parenchymal, leptomeningeal, dural or ependymal enhancement (Fig. 6). Although Wave-T1 SPACE images demonstrated slightly greater image noise, there was no impact on the overall diagnostic quality.

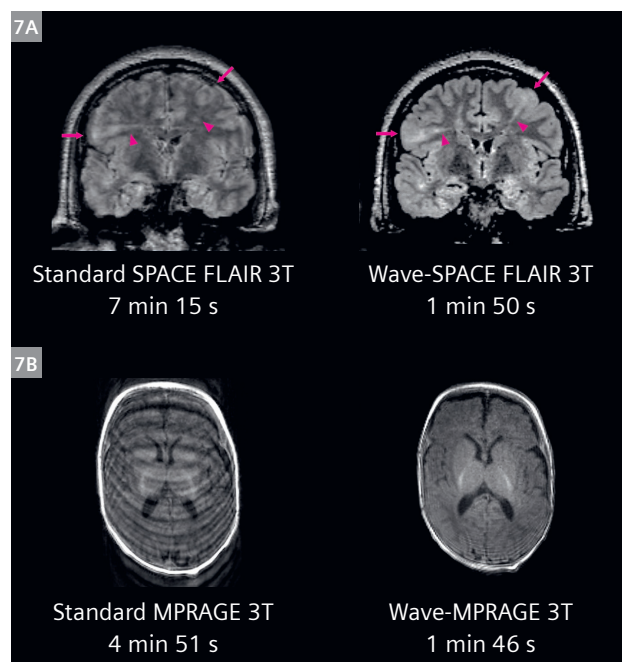
Rapid acquisition techniques not only shorten scan times to increase scanning efficiency but also provide higher-quality data through reducing vulnerability to motion (Fig. 7), artifacts arising from dynamic physiological changes, and blurring that accumulates with time during the image encoding [9]. We have observed further benefits in motion prone populations such as infants and children<sup>2</sup>, and individuals with clinical conditions that limit their cooperation for long lasting exams (e.g., critically ill patients in the emergency department or intensive care unit).

**Table 5:** Representative acquisition parameters of standard and accelerated 3D T1 SPACE sequences performed on a 3T MAGNETOM scanner with 20-channel and 32-channel coil arrays.

	FOV read (mm)	FOV phase (%)	Matrix size	Slice thickness (mm)	TR/TE (msec)	Flip angle (degree)	Acceleration factor <i>R</i>		Scan time	
							20-ch	32-ch	20-ch	32-ch
Standard T1 SPACE	230	89.8	256 x 256	0.9	700/11	120	GRAPPA, <i>R</i> = 4	GRAPPA, <i>R</i> = 4	4 min 19 s	4 min 19 s
Wave-T1 SPACE	240	100	256 x 256	1	700/12	120	Wave-CAIPI, <i>R</i> = 9	Wave-CAIPI, <i>R</i> = 9	1 min 40 s	1 min 40 s



**6** Comparison of abnormal enhancement in (6A) glioblastoma presenting as a large parenchymal mass in the cerebral hemisphere, (6B) multiple nodular leptomeningeal enhancing lesions due to leptomeningeal spread of lymphoma throughout the bilateral cerebellar hemispheres, and (6C) a heterogeneously enhancing melanoma metastasis in the cerebellar hemisphere with dural enhancement in the overlying tentorium (arrowheads) on standard T1 SPACE and Wave-T1 SPACE at 3T with a 32-channel coil array.



**7** Rapid acquisition with Wave-CAIPI reduces vulnerability to motion artifacts, demonstrated by (7A) coronal standard SPACE FLAIR vs. Wave-SPACE FLAIR, exhibiting image degradation that impairs the evaluation of cortical tubers (arrows) and radial bands (arrowheads) in a patient diagnosed with tuberous sclerosis complex. (7B) Axial standard MPAGE vs. Wave-MPAGE demonstrating intense motion artifacts in a 3-month-old infant<sup>2</sup> being evaluated after seizures, showing an age-appropriate pattern of T1 hyperintense myelinated white matter in the posterior limbs of the internal capsules that is much better seen on the Wave-MPAGE exam.

## Conclusion

We have successfully used Wave-CAIPI to enable encoding-intensive high-resolution isotropic acquisitions across a variety of contrasts and clinical indications. The highly accelerated Wave-CAIPI examinations preserve image quality and achieve comparable diagnostic performance to the comparison standard protocol with a 2- to 5-fold reduction in scan time, depending on the pulse sequence, RF coil and field strength. The increasing interest and demand for fast brain imaging examinations ensures that Wave-CAIPI technology will benefit a wide range of individuals including motion-prone populations while decreasing the time that patients are in the scanner, thereby improving patient comfort, throughput and facilitating the more efficient use of valuable MRI resources.

## Acknowledgments

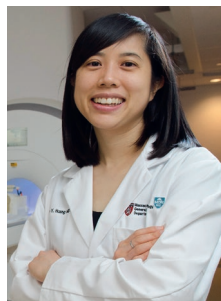
The authors would like to thank Maria Gabriela Longo, John Kirsch, Chanon Ngamsombat, Paul Caruso, Michael Gee, and Azadeh Tabari for their valuable support.

## References

- 1 Setsompop K, Feinberg DA, Polimeni JR. Rapid brain MRI acquisition techniques at ultra-high fields. *NMR Biomed*. 2016; 29: 1198–1221.
- 2 Bilgic B, Gagoski BA, Cauley SF, et al. Wave-CAIPI for Highly Accelerated 3D Imaging. *Magn Reson Med*. 2015; 73: 2152–2162.
- 3 Cauley SF, Setsompop K, Bilgic B, Bhat H, Gagoski B, Wald LL. Autocalibrated wave-CAIPI reconstruction; Joint optimization of k-space trajectory and parallel imaging reconstruction. *Magn Reson Med*. 2017;78(3):1093-1099. doi:10.1002/mrm.26499
- 4 Conklin J, Longo MGF, Cauley SF, et al. Validation of Highly Accelerated Wave-CAIPI SWI Compared with Conventional SWI and T2\*-Weighted Gradient Recalled-Echo for Routine Clinical Brain MRI at 3T. *AJNR Am J Neuroradiol*. 2019; 40:2073–80.
- 5 Polak D, Setsompop K, Cauley SF, et al. Wave-CAIPI for highly accelerated MP-RAGE imaging. *Magn Reson Med*. 2018;79(1):401-406.
- 6 Longo MGF, Conklin J, Tian Q, et al. Validation of ultrafast Wave-CAIPI magnetization prepared rapid gradient-echo (MPRAGE) for quantitative evaluation of brain tissue volume in the workup of suspected neurodegenerative disease. *American Society of Neuroradiology*, 2019. Boston, MA.
- 7 Ngamsombat C, Longo MGF, Goncalves Filho ALM, et al. Evaluation of Ultrafast Wave-CAIPI Three-Dimensional Fluid-attenuated Inversion Recovery (3D FLAIR) Compared to Standard 3D FLAIR for Quantitative Analysis of Cerebral White Matter Lesions. Accepted for oral presentation at the Annual Meeting of the American Society of Neuroradiology, Las Vegas, Nevada. May 30–June 04, 2020.
- 8 Goncalves Filho ALM, Longo MGF, Conklin J, et al. Evaluation of Highly Accelerated Wave-CAIPI Post-Contrast 3D-T1 Sampling Perfection With Application Optimized Contrast Using Different Flip-Angle Evolutions (Wave-3D-T1 SPACE) Compared to Standard Post-Contrast 3D-T1 SPACE for Detection of Intracranial Enhancing Lesions. Accepted for oral presentation at the Annual Meeting of the American Society of Neuroradiology, Las Vegas, Nevada. May 30–June 04, 2020.
- 9 Polak D, Cauley SF, Huang SY, et al. Highly-Accelerated Volumetric Brain Examination Using Optimized Wave-CAIPI Encoding. *J. MAGN. RESON. IMAGING*. 2019; 50:961–974.

## Contact

Susie Y. Huang, MD, PhD  
 Assistant Professor of Radiology, Harvard Medical School  
 Radiologist, Division of Neuroradiology  
 Director of Translational MR Imaging  
 Athinoula A. Martinos Center for Biomedical Imaging  
 Department of Radiology, Massachusetts General Hospital  
 Building 149, Room 2.301  
 Charlestown, MA 02129  
 USA  
[susie.huang@mgh.harvard.edu](mailto:susie.huang@mgh.harvard.edu)



<sup>2</sup>MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures.

