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

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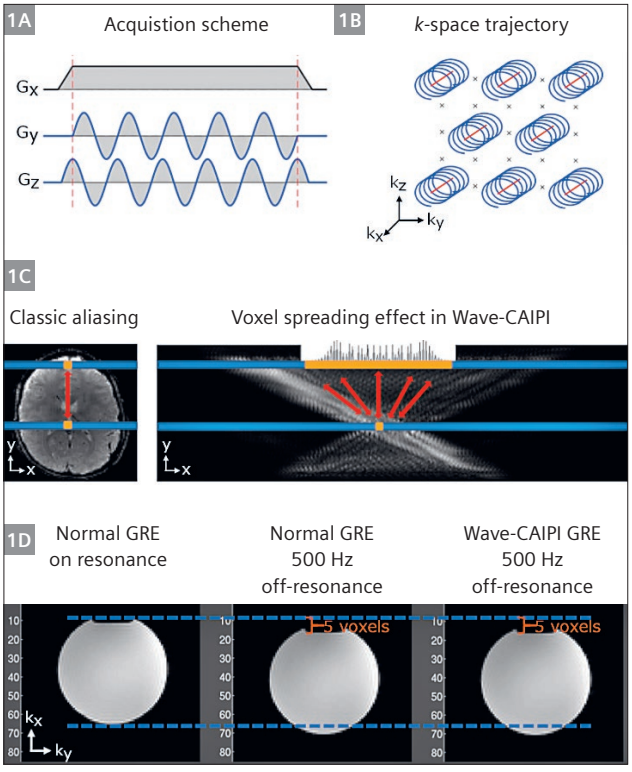
Introduction

Parallel imaging techniques (e.g., SENSE [1], GRAPPA [2], etc.) have enabled substantial scan time reduction in Magnetic Resonance Imaging (MRI) while retaining high spatial resolution and appropriate imaging contrast. These methods leverage the spatial information afforded by multi-channel receiver arrays to minimize the time-consuming gradient encoding. However, the performance of these acceleration techniques is limited by the spatial encoding capability of the coil sensitivities which are related to the coil design and coil geometry (adjacent coil elements typically have similar coil sensitivity). In the case of conventional 2D slice-by-slice imaging, the close spatial proximity of aliased voxels usually constrains clinical applications to moderate acceleration factors, even when a modern high-channel-count receive array is used.

Several new imaging technologies have been developed to address the increasing encoding burden at high resolution and enable faster scanning. This represents a move towards volumetric imaging, where Simultaneous MultiSlice (SMS) and efficient 3D-encoding have enabled dramatic increases in acquisition speed. These imaging techniques can also make better use of the coil sensitivity information in multi-channel receiver arrays, i.e. through employing controlled aliasing along multiple spatial dimensions. The 2D-CAIPIRINHA technique [3] was developed to enable higher acceleration for 3D acquisitions by employing a staggered k_y-k_z undersampling pattern. This increases the distance between aliased voxels in the phase-partition encoding plane allowing for better utilization of the available variation in the coil sensitivity profiles.

The recently proposed Wave-CAIPI[1] technique [4] expands controlled aliasing to the full 3D extent. This has enabled even greater parallel imaging encoding capability for structural scans while retaining good image quality and SNR.



1 Wave-CAIPI:
(1A) Wave-CAIPI utilizes sinusoidal gradients during the frequency encoding. **(1B)** The sinusoidal waveforms incur corkscrew trajectories in *k*-space which are staggered due to the 2D-CAPIRINHA sampling **(1C)** In the image domain Wave-encoding results in voxel spreading along the readout direction. This increases the distance between collapsing voxels when compared to classic aliasing. **(1D)** Wave-CAIPI exhibits the same off-resonance shifts along the readout direction as standard Cartesian acquisitions (here shown for GRE at 500 Hz off-resonance and bandwidth 100 Hz/px).

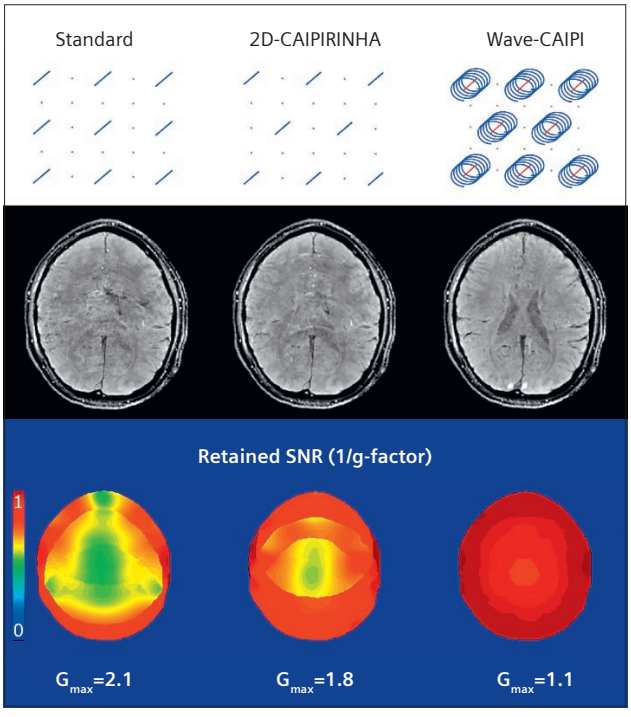
[1]*Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Wave-CAIPI

Wave-CAIPI [4] generalizes 2D-CAIPIRINHA and Bunch Phase Encoding/Zig-Zag sampling [5, 6] to create a controlled aliasing concept that encompasses all three spatial dimensions (including the readout direction). Figure 1A demonstrates the acquisition scheme for Wave-CAIPI. Two sinusoidal gradients G_y and G_z are played during the readout with a quarter cycle phase shift. Combined with 2D-CAIPIRINHA sampling, this results in staggered corkscrew trajectories through *k*-space (Fig. 1B). In the image domain the additional phase deposition results in voxel-spreading along the readout direction which varies linearly as a function of the spatial y and z position (Fig. 1C). When combined with the interslice shifts from 2D-CAIPIRINHA, a well distributed aliasing pattern is created across all three spatial dimensions. This allows Wave-CAIPI to take full advantage of the 3D coil sensitivity information and enables up to an order of magnitude increase in acquisition speed with negligible parallel imaging noise amplification and artifact penalty [4, 7–9].

Wave-CAIPI also has several desirable properties that enable high quality reconstruction. In contrast to other rapid acquisition techniques such as EPI or spiral imaging, Wave-CAIPI is not susceptible to image blurring and distortion artifacts caused by inhomogeneity of the main magnetic field (B0) [9]. This can be attributed to the constant rate of *k*-space traversal along the readout direction (k_x) for Wave-CAIPI. As a result, phase evolution from B0 inhomogeneity only evolves as a function of k_x, resulting in the same chemical shift effect as observed in conventional Cartesian imaging sequences. This effect is demonstrated in Figure 1D. At 500 Hz off-resonance a Wave-CAIPI gradient echo (GRE) acquisition shows the same voxel shift along the readout direction as a standard acquisition. Moreover, intravoxel dephasing is negligible in Wave-CAIPI acquisitions as sinusoidal waveforms prevent large accrual of the gradient moment [4].

Figure 2 compares the encoding efficiency of Wave-CAIPI, 2D-CAIPIRINHA and standard acquisitions at R = 3 x 3 acceleration and 1 mm³ isotropic resolution using a Siemens Healthineers 32-channel head coil. Wave-CAIPI offers high quality reconstructions and negligible noise amplification penalty as evidenced by the reciprocal *g*-factor maps (measure of noise amplification due to lack of spatial encoding). In contrast, 2D-CAIPIRINHA and standard sampling provide insufficient encoding capability at R = 9-fold acceleration causing residual aliasing artifacts and large noise amplification especially in the center of the brain.



2 ***G*-factor comparison at R = 3 x 3:** At R = 3 x 3 acceleration, standard and 2D-CAIPIRINHA sampling result in residual aliasing artifacts and large noise amplification especially in the center of the brain. In contrast, Wave-CAIPI yields high quality reconstructions without artifacts and close to perfect *g*-factor.

Auto-calibrated image reconstruction

Wave-CAIPI acquisitions can be reconstructed efficiently using a generalized SENSE framework thus avoiding the need for *k*-space gridding [4]. This is made possible as the non-Cartesian corkscrew trajectory can be represented as additional phase deposition in Cartesian *k*-space. Using a simple point spread function framework, the voxel spreading effect from Wave-CAIPI is either modeled as a spatially varying convolution in the image domain or more efficiently as a phase modulation in hybrid space (k_x, y, z). Due to this spatially invariant encoding property, the SENSE-based reconstruction also remains highly separable. This allows for efficient parallelization as separate linear systems can be solved for each set of collapsing readout lines. Moreover, Wave-CAIPI does not require internal calibration data, as volumetric ESPIRiT [10] coil sensitivity maps are typically computed from a rapid low-resolution 3D gradient echo (GRE) scan (acquisition time roughly two seconds).

The separable Wave-CAIPI reconstruction also facilitates the automatic estimation and correction of any minor gradient deviations from the nominal trajectory without the need for additional calibration scans. This auto-calibrated technique [11] relies on a compact representation of the Wave-encoding's sinusoidal phase modulation (including minor deviations) which can be accurately described using a limited number of frequency coefficients. To accurately determine the exact *k*-space

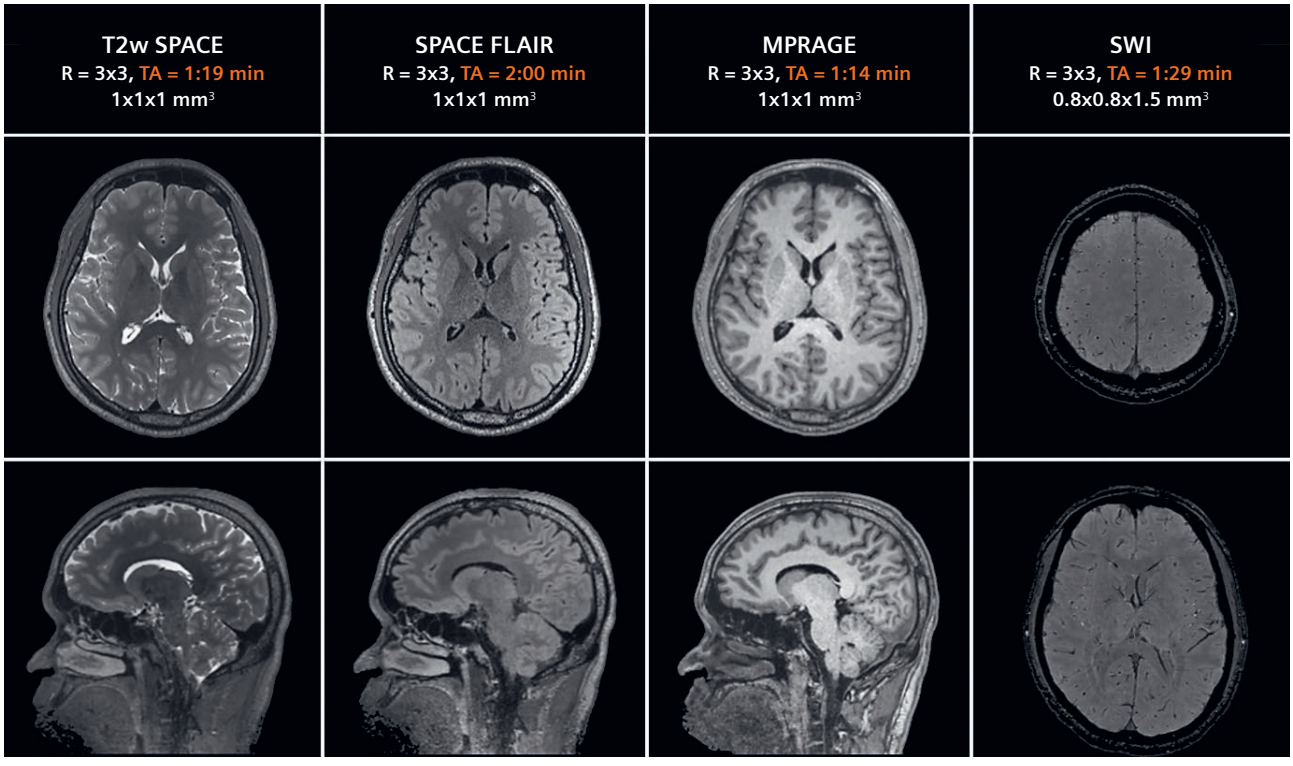
trajectory, the auto-calibrated reconstruction optimizes the frequency coefficients and aliased voxels jointly to reduce the data consistency error of the generalized SENSE encoding model. By limiting this non-linear search to a small representative set of collapsing readout lines, the computational demand of this optimization problem is substantially reduced while mitigating artifacts globally. This has enabled rapid convergence (roughly after 10 seconds) for arbitrary acquisition protocols using standard scanner computation hardware.

Applications

The Wave-CAIPI acquisition and reconstruction framework can be broadly applied and has been shown to enable up to an order of magnitude higher acceleration for both SMS and 3D imaging sequences [4, 7–9] with negligible *g*-factor noise amplification. This scan efficiency has allowed for the development of a six-minute high-resolution volumetric brain exam comprising of the clinical contrasts T1w MPRAGE, T2w SPACE, T2w SPACE-FLAIR and T2*w SWI. Detailed optimization of the Wave corkscrew was performed for each structural scan to achieve optimal performance with respect to SNR and image quality [8]. Figure 3 illustrates example slices acquired at 3T (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) using a product Siemens Healthineers 32-channel head coil. Good SNR and contrast are provided in each of the rapid volumetric acquisitions (scan time 1–2 minutes each). Due to the isotropic resolution ($1 \times 1 \times 1$ mm^3) of MPRAGE and SPACE (T2w and FLAIR) these datasets can also be reformatted and viewed in arbitrary orientations without loss of spatial resolution.

The encoding capability of Wave-CAIPI can also be deployed in clinical standard protocols with high in-plane resolution and thick slices [12]. In Figure 4, Wave-CAIPI SPACE-FLAIR (R = 3 x 2, 0.8 x 0.8 x 3 mm^3) was acquired in axial orientation and compared to standard clinical T2w TSE (R = 2). Despite substantial speed-up from Wave-encoding, comparable contrast and image quality is maintained.

At present, clinical validation of the rapid Wave-CAIPI sequences for brain imaging is being led by the Neuroradiology Department of the Massachusetts General Hospital (Boston, MA, USA). The objective of these ongoing assessments is to establish non-inferior diagnostic quality between the Wave-CAIPI and standard clinical protocols routinely used at this institution. Progress towards this goal has been reported in several clinical evaluations [13–16] and is also summarized in "Ultrafast



3 **Six-minute volumetric whole brain exam using Wave-CAIPI:**
Six-minute high-resolution whole-brain exam comprised of T2w SPACE, T2w SPACE-FLAIR, T1w MPRAGE and T2*w SWI at R = 9-fold acceleration.

Multi-contrast High-resolution 3D Brain MRI: Clinical Evaluation of Wave CAIPI Acceleration in SWI, MPRAGE, FLAIR, SPACE" by Susie Huang et al. available at: www.siemens.com/magnetom-world > Clinical Corner > Case Studies.

Acknowledgments

The authors would like to thank Wei Liu, Daniel Nicolas Splitthoff, Borjan Gagoski, Wei-Ching Lo, Sinyeob Ahn, Thomas Beck, Thorsten Feiweier, Himanshu Bhat, Yulin Chang, Shivraman Giri and Keith Heberlein for their valuable support.

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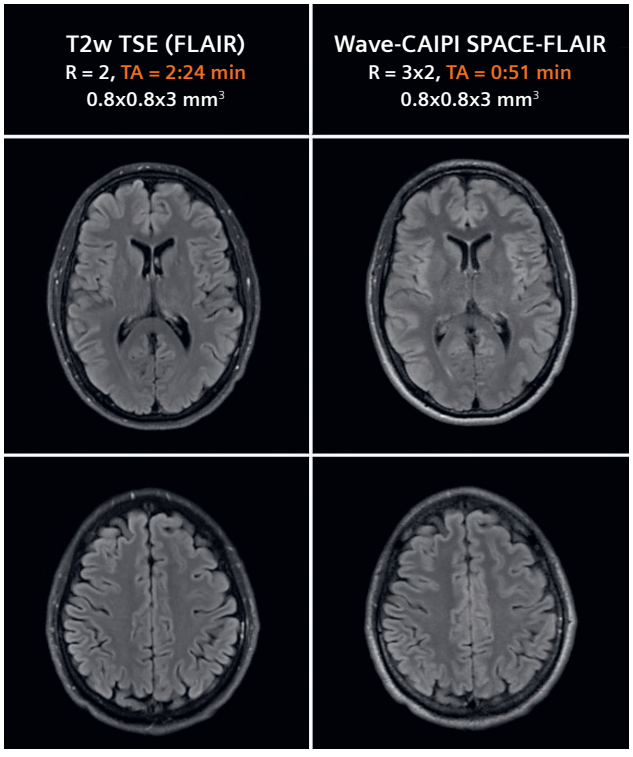

4 **Comparing standard T2w TSE versus Wave-CAIPI SPACE-FLAIR:** Standard clinical T2w TSE scan is compared to highly accelerated 3D Wave-CAIPI SPACE-FLAIR acquisition with high in-plane resolution and thick slices.

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