Combined Compressed Sensing-CAIPIRINHA DESS with Deep Learning Reconstruction for Highly Accelerated 7T MR Neurography

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Introduction

Magnetic resonance neurography of the cervical spine greatly benefits from the signal-to-noise ratio available at 7T. The 3D double-echo steady-state (DESS) sequence with water excitation provides excellent visualization of cervical nerve anatomy and intervertebral discs while effectively suppressing surrounding bone and fat tissue [1]. This enables high-contrast images that clearly depict micro-structural detail such as intradural rootlets/roots, dorsal root ganglia (DRGs), and the proximal spinal nerves [2, 3]. A key challenge, however, is the relatively long acquisition time required to achieve the necessary sub-millimeter isotropic resolution. Extended scan durations make the examination more vulnerable to motion artifacts caused by swallowing, breathing, or cerebrospinal fluid pulsation.

Substantial reductions in scan time can be achieved through coherent (e.g., GRAPPA, CAIPIRINHA) [4, 5] and incoherent (compressed sensing [CS]) undersampling [6] combined with deep learning (DL) reconstruction. Combining CAIPIRINHA and CS with DL reconstruction may enable even greater acceleration while preserving or improving image quality [7] compared to state-of-the-art CAIPIRINHA or CS.

We explored a novel joint CS + CAIPIRINHA (CS-CAIPI) data sampling scheme with DL reconstruction for highly accelerated 3D DESS MR neurography[1] at 7T.

Parameter	DESS
TR/TE (ms)	8.0 / 3.0
Flip angle (°)	15
Receiver bandwidth (Hz/Px)	434
Number of slices	384
Reconstructed voxel size (mm³)	0.35 × 0.35 × 0.35
FOV (mm²)	180 × 180
Acquisition matrix	256 × 256
Fat-water contrast	water excitation
Phase oversampling (%)	40
Phase encoding direction	right-left
Imaging plane orientation	coronal

Table 1: Acquisition parameters for the 7T double-echo steady-state sequence (DESS).
Acquisition parameters for the 3D DESS sequence were kept constant across acceleration factors and undersampling schemes.
FOV = field of view; TE = echo time; TR = repetition time

[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.*

Material and methods

Image acquisition and reconstruction
Two healthy volunteers underwent 7T cervical spine MRI on the MAGNETOM Terra.X (Siemens Healthineers, Erlangen, Germany) using an 8Tx/8Rx neck coil (Rapid Biomedical, Rimpar, Germany).

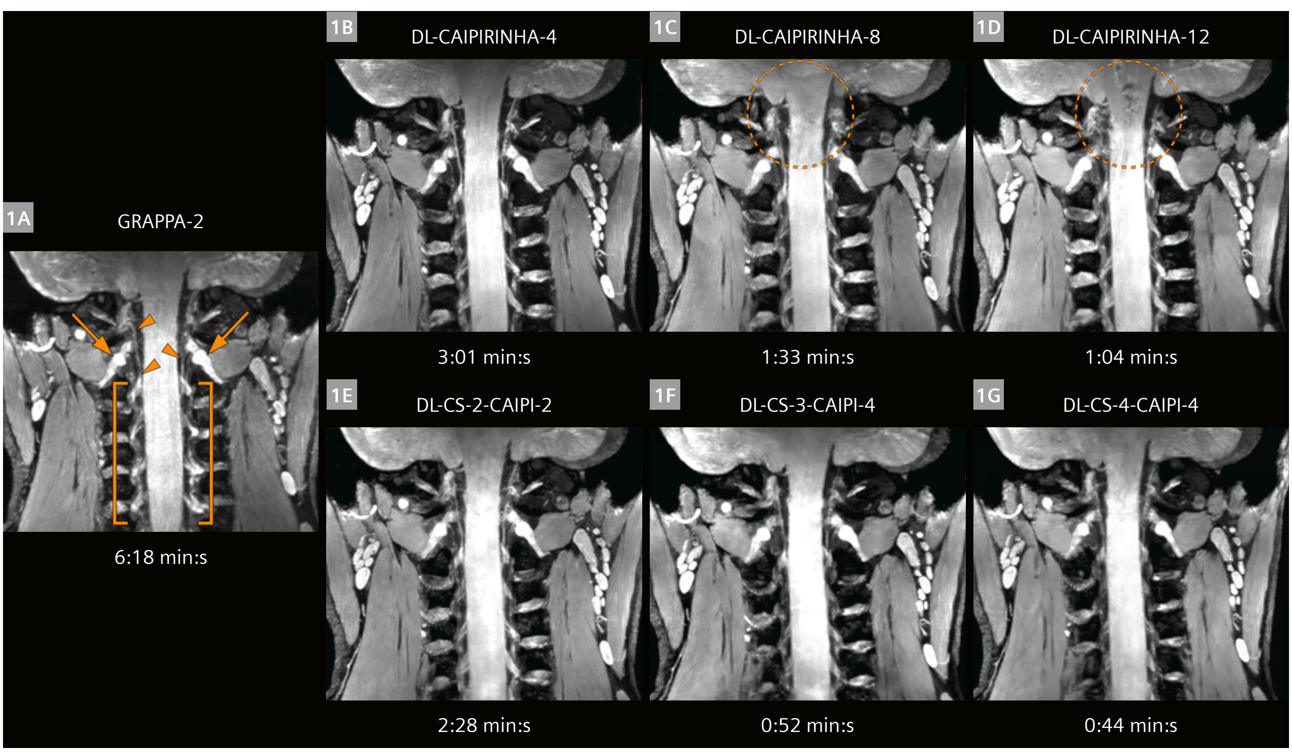
A 3D DESS sequence with conventional 2-fold GRAPPA acceleration served as the reference. The sequence was then repeated with a research application sequence[1] featuring CAIPIRINHA-only undersampling (DL-CAIPIRINHA) and combined CAIPIRINHA + CS undersampling (DL-CS-CAIPI) with DL reconstruction, while keeping all other parameters identical (Table 1). Acceleration factors were progressively increased (DL-CAIPIRINHA: R = 2–12; DL-CS-CAIPI: R = 4–16).

The combined undersampling scheme first applies a regular CAIPIRINHA pattern, then superimposes a variable-density Poisson-disc (CS) mask. Total acceleration is the product of the two factors ($R_{Total} = R_{CAIPIRINHA} \times R_{CS}$). The reconstruction uses a two-stage pipeline: initial CS reconstruction with redundant Haar wavelets (FISTA optimization) [8] followed by DL-based refinement [9] inspired by variational networks (trained on fully sampled 1.5T/3T data and fine-tuned on 7T data). Acquisition times decreased from 6:18 minutes (GRAPPA-2) to only 44 seconds with 16-fold DL-CS-CAIPI.

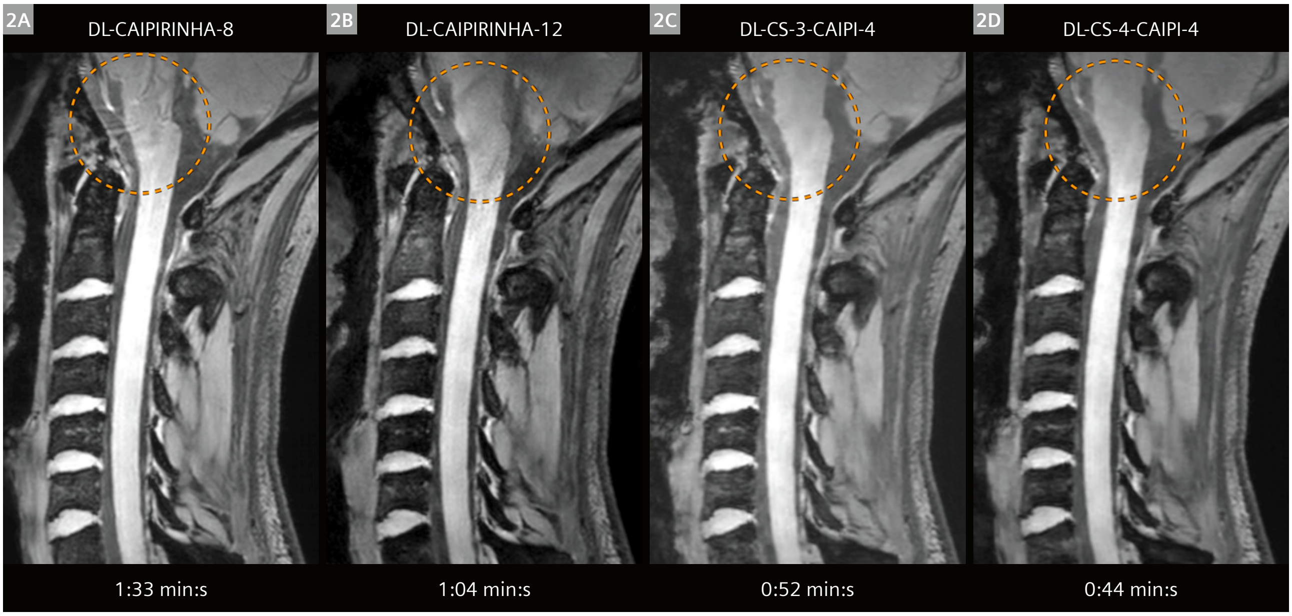
Images were reviewed with a focus on overall quality, noise, artifacts, and sharpness of neural structures.

Results

Figures 1 and 2 show representative images from two healthy volunteers, illustrating the performance of the different undersampling schemes across a range of acceleration factors. Optimal image quality and neural-structure sharpness were observed with 4-fold DL-CAIPIRINHA compared with the standard GRAPPA reference, with a 50% shorter scan time and markedly reduced motion artifacts.



1 Coronal 3 mm maximum intensity projections of 3D DESS images acquired using 2-fold GRAPPA **(1A)**, DL-CAIPIRINHA **(1B–D)**, and combined DL-CS-CAIPI **(1E–G)** at progressively higher acceleration factors with their corresponding acquisition times. The 2-fold GRAPPA image **(1A)** depicts the bilateral C2 dorsal root ganglia (arrows), C3–C6 intraspinal rootlets/roots (brackets), and spinal roots of the spinal accessory nerve (arrowheads). Neural-structure sharpness is improved with 4-fold DL-CAIPIRINHA **(1B)**. At higher CAIPIRINHA-only accelerations (R = 8 and R = 12 in **1C** and **1D**), streak-like aliasing artifacts become visible (circles). The combined DL-CS-CAIPI technique maintains good overall anatomic detail, although some blurring appears at R = 12 and R = 16 **(1F, 1G)**.



2 Sagittal 3D DESS images acquired using DL-CAIPIRINHA at R = 8 and R = 12 **(2A, 2B)** and combined DL-CS-CAIPI at R = 12 and R = 16 **(2C, 2D)** with their corresponding acquisition times. Streak-like aliasing artifacts around the brainstem (circles in **2A** and **2B**) compromise image quality with DL-CAIPIRINHA alone. In contrast, the combined DL-CS-CAIPI approach shows only a mild and less disruptive "leopard-like" speckled pattern at the brainstem (circles in **2C** and **2D**), even at the extreme acceleration of R = 16.

At higher accelerations (particularly at R ≥ 8), however, standalone DL-CAIPIRINHA suffered from increasing streak-like aliasing artifacts, pronounced around the brainstem and image periphery.

The combined DL-CS-CAIPI DESS proved more robust at acceleration factors beyond R = 8. Image quality remained comparable to GRAPPA-2 until 12-fold DL-CS-3-CAIPI-4, despite a 6-fold reduction in scan time. Although combined DL-CS-CAIPI schemes demonstrated higher baseline reconstruction artifact levels (mainly blurring, speckled pattern), they had fewer severe reconstruction artifacts at R = 12 and R = 16 compared with DL-CAIPIRINHA-12. The main trade-off for DL-CS-CAIPI at high acceleration was increased blurring beyond R = 8, leading to reduced edge sharpness of neural structures compared with standalone DL-CAIPIRINHA at equivalent total acceleration.

Conclusion

Coherent CAIPIRINHA undersampling combined with DL reconstruction delivered superior image quality in 7T MR neurography while halving acquisition time compared with conventional GRAPPA. The addition of incoherent CS undersampling enabled high accelerations (R ≥ 8) with a more favorable artifact profile, replacing the structured aliasing artifacts seen in CAIPIRINHA-only acceleration with subtler, less disruptive "leopard-like" patterns [10].

The novel integration of coherent and incoherent undersampling in a combined CS-CAIPI framework with DL reconstruction provides a robust approach for preserving image quality at acceleration factors beyond R = 8. It enables efficient high-resolution cervical spine MRI with up to a 6-fold reduction in scan time.

In summary, our initial experience suggests that the synergistic combination of CS-CAIPI and DL reconstruction makes highly accelerated, high-resolution 7T MR neurography of the cervical spine feasible while preserving anatomic detail.

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