Compressed Sensing: Application to Time-of-Flight MR Angiography

Takayuki Yamamoto; Tomohisa Okada; Koji Fujimoto; Yasutaka Fushimi; Akira Yamamoto; Kaori Togashi

Department of Diagnostic Imaging and Nuclear Medicine, Kyoto University, Japan

Introduction

Time-of-Flight MR Angiography (TOF MRA) is a reliable method to visualize the cerebral vasculature and is widely used in clinical practice. It is a non-invasive technique, which is free from radiation exposure and adverse effects of contrast materials. The main concerns of high-resolution TOF MRA are its long scan time and decreased signal-to-noise ratio (SNR).

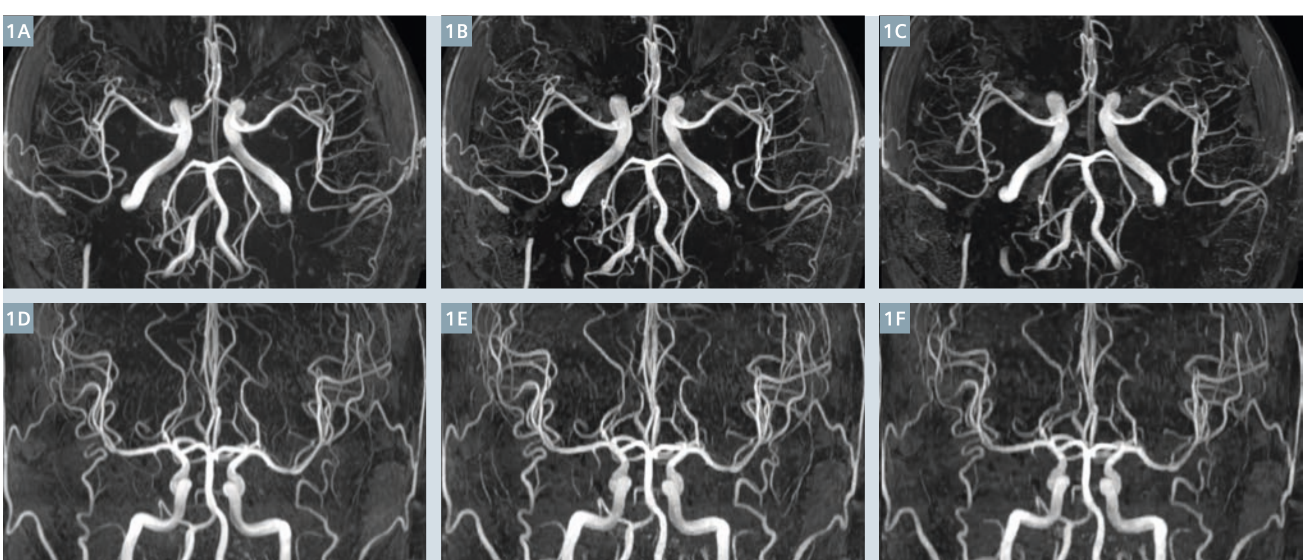
Compressed Sensing (CS) provides a novel approach to restore the original image quality from fewer *k*-space acquisitions by exploiting intrinsic sparsity in the imaged object combined with iterative reconstruction and its denoising capabilities. MRA is a good candidate for CS because of the high signal in the vessels which are sparse in space [1]. The combination of parallel acquisition (PAT) and CS can significantly reduce the examination time [3].

Scan time reduction is important not only for economic reasons but also to reduce the burden on the patient and to limit motion artifacts which can disrupt vascular depictions. In this case study, we will describe our early experiences with Compressed Sensing (CS) TOF[1] MRA in various clinical patients to visualize the cerebral arteries.

Compressed Sensing TOF technique

For data acquisition, a conventional 3D TOF gradient-echo sequence was combined with random sampling. For this purpose, the *k*-space of each imaging slab was sub-sampled in the k_y-k_z phase-encoding direction with a variable density Poisson disk sampling pattern. In the pattern, the sampling density was gradually increased from periphery toward the center of *k*-space to optimize the acquisition of data in high image-energy central *k*-space regions and hence enhance the signal-to-noise ratio (SNR). The incoherence of the random sampling pattern would lead to artifacts that scatter across the whole image in a 'noise-like' manner after Fourier transform. A fully sampled region in the center of *k*-spacewas utilized to estimate the coil sensitivity maps.

[1] WIP, Compressed Sensing TOF is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.



1 Axial **(1A-C)** and coronal **(1D-F)** MIP images of a healthy subject (35-year-old, male) reconstructed from full-sampling data **(1A, D)**, 3.4-fold net acceleration **(1B, E)**, and 6.4-fold net acceleration **(1C, F)**, respectively.

After data acquisition, the image can be recovered from the subsampled data by nonlinear, iterative reconstruction. In this reconstruction, the images were reconstructed by solving the following minimization problem [4-6]:

$$\min_x \|Ax - y\|_2^2 + \lambda \, \|\Phi(x)\|_1$$

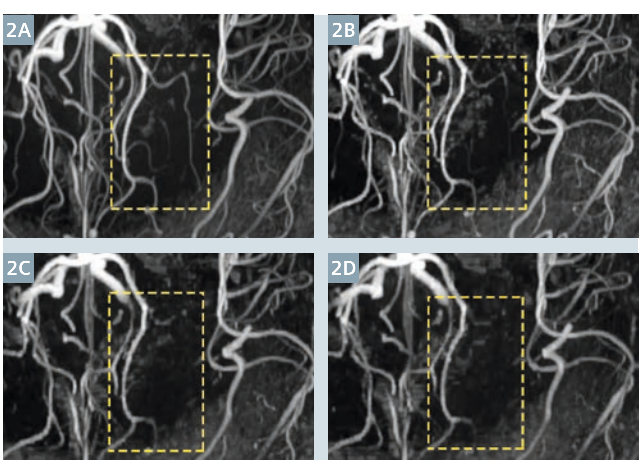
where y is the acquired *k*-space data and x the estimated image. The system matrix, A, describes the data acquisition process, which is required for the comparison of the image and acquired data. The transform sparsity term enforces a sparse representation of the image. For this purpose, the image is transformed a sparse representation by $\Phi(\cdot)$, for example, using the redundant Haar wavelet transform. The balance between data fidelity and sparsity is adjusted with the regularization parameter λ, which was empirically set to 0.0002. The iterative reconstruction process was terminated after 20 iterations.

Imaging was performed at a clinical 3T MR scanner (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) with a 32-channel head coil. Parameters for the imaging protocol were TR 20 ms, TE 3.7 ms, flip angle 18° and bandwidth 189 Hz/Px. In total, 5 slabs were acquired with 20% slice oversampling with a matrix of 384 x 326 x 90 and a voxel size of 0.3 x 0.3 x 0.35 mm (FOV 220 x 190 cm). The images of conventional TOF imaging with a PAT factor of 2 and 3 were compared to those acquired with CS TOF featuring acceleration rates from 3.4 up to 6.4.

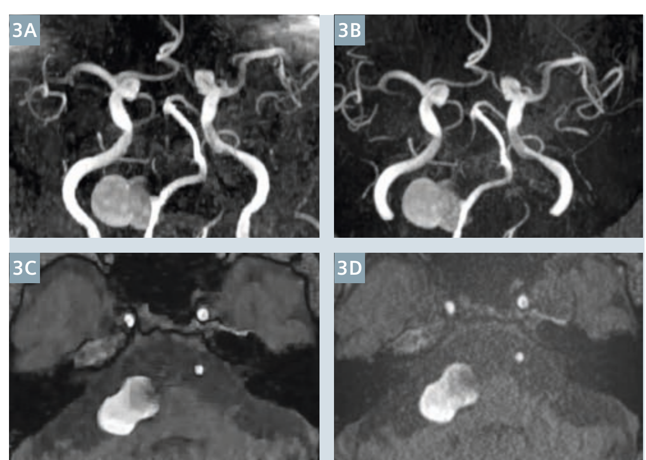
Image reconstruction was done directly on the scanner with standard hardware.

Imaging examples of cerebral angiography with CS TOF

Figures 1 and 2 show images of healthy subjects. On maximum intensity projection (MIP) images, cerebral arteries are well visualized in CS TOF images with acceleration rates from 3.4 up to 6.4 (Fig. 2). Although the



2 Magnified view of MIP images for the same subject as in Figure 1. Net acceleration rates are **(2A)** full sampling, **(2B)** 3.4, **(2C)** 6.4, and **(2D)** 7.1. Most of the arterial branches are visualized well, but small branch with lower signal is a challenge for CS TOF (shown with rectangles in yellow dashed lines).



3 An aneurysm of the right vertebral artery in a 68-year-old male. **(3A, C)** CS TOF with net acceleration rate of 6.1, and **(3B, D)** conventional TOF MRA (using PAT factor of 3 in the phase encoding direction and partial Fourier of 7/8) with a net acceleration rate of 3.

depiction of distal branches becomes weaker at a higher acceleration rate (Fig. 3), the visualization of proximal branches was acceptable, which is important to diagnose the steno-occlusive diseases or cerebral aneurysms. We have previously reported that the diagnostic quality of distal branches was maintained with a nominal acceleration factor of 6, which achieved a shorter acquisition time of less than half of the conventional PAT acceleration of 2 [1].

Figures 3 through 6 show cases in clinical practice. The result images of CS TOF and conventional TOF are displayed side by side to facilitate comparison of vascular shape. Conventional TOF used modified GRAPPA (acceleration factor of 3) and partial Fourier technique (7/8 for the phase and the slice direction). A net acceleration rate of 6.1 was used for CS TOF for all cases. The matrix size of conventional TOF was kept the same as CS TOF, but the number of slabs was 3, which was set to 5 for CS TOF. The acquisition time for conventional TOF was 3 min 11 sec.

Conclusion

CS TOF can drastically reduce the scan time while minimizing loss of image quality at high acceleration rates. In some cases, residual sub-sampling artifacts remain in the reconstructed images, however without influencing the image quality of the MIP angiogram remarkably. The first experiences indicate that a diagnostic image quality can be achieved in a clinical setting using highly accelerated CS TOF for the visualization of cerebral arteries. Our results warrants future larger clinical studies in a larger cohort to find the optimal balance between acquisition speed and high resolution.

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Case 1

68-year-old male was followed up for a large aneurysm of the right vertebral artery for several years (Fig. 4). The aneurysm gradually increased in size, and the patient was admitted to our hospital. The size and the gourd-like shape of the aneurysm are well depicted in CS TOF. There is almost no difference in the MIP image between CS TOF and conventional TOF, although CS TOF is twice as fast.

4 Two aneurysms of the right internal carotid artery (arrows). **(4A)** CS TOF with a net acceleration rate of 6.1 and **(4B)** conventional TOF with a net acceleration rate of 3.

Case 2

78-year-old female was admitted to our hospital because of left hemiplegia. Two aneurysms in the right internal carotid artery (Fig. 5) are incidentally found. Both aneurysms are well visualized in spite of their small size.

5 Stenosis of the left internal carotid artery (circle). **(5A)** CS TOF with a net acceleration rate of 6.1 and **(5B)** conventional TOF with a net acceleration rate of 3.

Case 3

74-year-old male with diabetes mellitus. The routine examination for diabetes revealed a severe stenosis of the left internal carotid artery (Fig. 6). The lesion is similarly depicted both in CS TOF and conventional TOF. Arterial irregularity is additionally seen at the proximal portion of right internal carotid artery only in CS TOF, which gives the impression of stronger stenotic change. An influence of motion is possibly suspected.

6 Stenosis of the left middle cerebral artery (arrows). **(6A)** CS TOF with a net acceleration rate of 6.1 and **(6B)** conventional TOF with a net acceleration rate of 3.

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Takayuki Yamamoto

Tomohisa Okada

Koji Fujimoto

Yasutaka Fushimi

Akira Yamamoto

Kaori Togashi

Contact

Tomohisa Okada, M.D., Ph.D.
Human Brain Research Center
Graduate School of Medicine
Kyoto University
54 Shogoin-Kawaharacho,
Sakyo-ku
Kyoto 606-8507
Japan
tomokada@kuhp.kyoto-u.ac.jp