A Highly-Accelerated Image Reconstruction Method by Simultaneous Encoded Slices with CAIPI in FMRI

Ke Xu[1] and Daniel B. Rowe[1,2]

[1]Department of Mathematical and Statistical Sciences, Marquette University, Milwaukee, WI, USA
[2]Department of Biophysics, Medical College of Wisconsin, Milwaukee, WI, USA

INTRODUCTION

In Functional Magnetic Resonance Imaging (fMRI) studies, the time to measure a volume image is dependent upon how rapidly the necessary amount of data needed to reconstruct an image can be measured. In order to accelerate the number of images measured per unit of time, a topic of study has been to measure less data but still be able to reconstruct a high-quality image. In order to reconstruct images using less data, multiple receive coils are used where each coil measures sensitivity-weighted images. Initially, accelerated imaging was aimed at in-plane acceleration where lines of spatial frequency data are skipped, and each coil measured fewer lines of spatial frequency. In SENSitivity Encoding (SENSE) [1] and Parallel Imaging techniques [2], a single slice has been excited, and partial lines of *k*-space skipped, resulting in a sensitivity-weighted aliased image for each coil, that is combined into a single complete image. More recently, Simultaneous Multi-Slice (SMS) techniques were developed and discussed. The SMS technique allows for a more efficient approach to acquiring images. Multiple slices are acquired at the same time and aliased together in one excitation, and hence, the image-acquiring time will decrease significantly with a factor of the total number of aliased slices per unit of time. Thus, a through-plane imaging acceleration was achieved by SMS techniques. A novel SMS technique called A CAIPI Approach of Multi-Coil Separation of Parallel Encoded Complex-Valued Slices will be presented.

METHOD

CAIPIRINHA and CAIPIVAT: Imaging using SMS is widely used, and it allows for acquiring fMRI data with high resolution within a reduced repetition time (TR). One of the main considerations of SMS study is diminishing the influence of the geometry factor (*g*-factor) of the coil array. The imaging shifted technique of the new method is based on the "Controlled Aliasing In Parallel Imaging Results In Higher Acceleration" (CAIPIRINHA) [3] and the "MultiSlice CAIPIRINHA Using View Angle Tilting Technique" (CAIPIVAT) [4].

A unique image shift is accomplished by applying a specific phase modulation to each line in the *k*-space as in Figure 1. In the CAIPI study, the signal-to-noise (SNR) ratio is given by Eq 1

$$SNR_{CAIPI} = \sqrt{N_s}\frac{SNR_{Full}}{g_{CAIPI}\sqrt{R}} \quad . \tag{1}$$

The *g*-factor, which is given by $g_{CAIPI} = \sqrt{(S^H\Psi^{-1}S)^{-1}(S^H\Psi^{-1}S)}$, is not a constant number but varies across each voxel within the images. The short distance between two aliased voxels will increase the *g*-factor value and the corresponding SNR ratio will decrease. The image shifting technique will increase the distance between two aliased voxels, therefore reducing the *g*-factor influence.

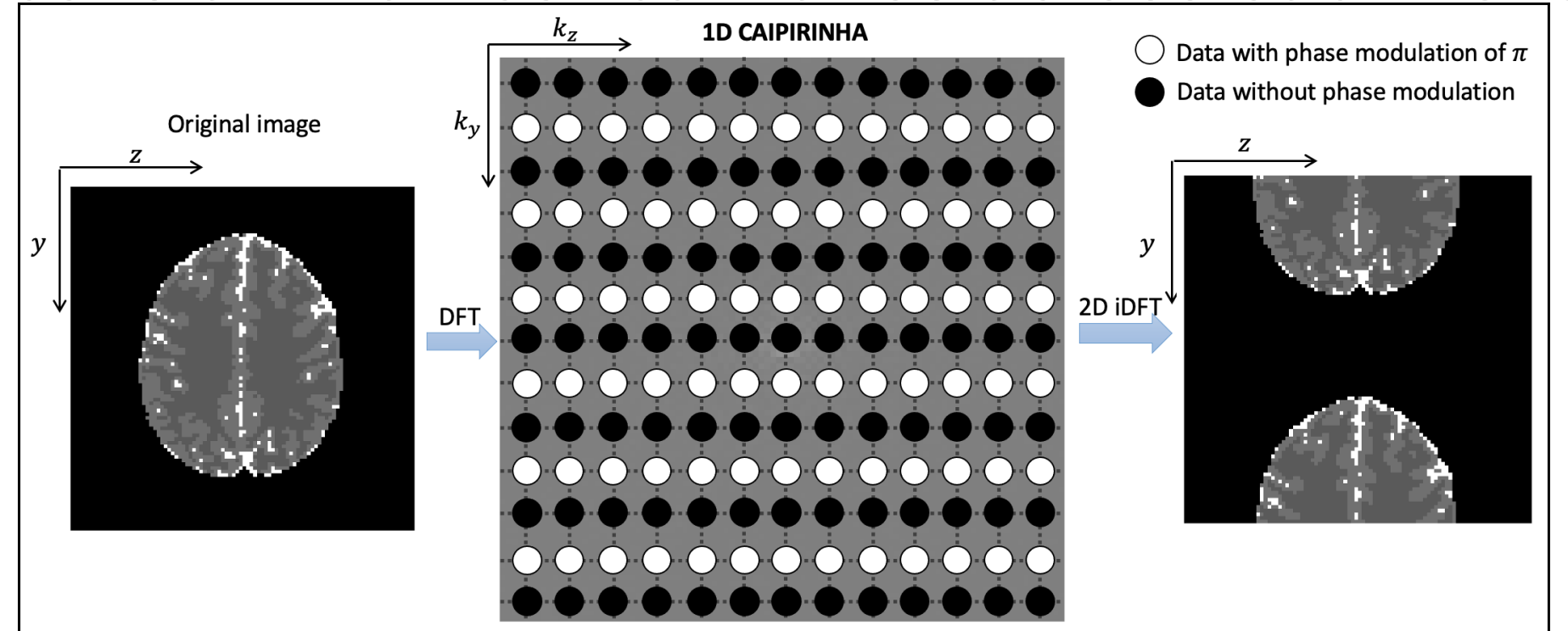

Figure 1: The 1D CAIPIRINHA diagram. Every odd line in *k*-space is unchanged and the phase of every even line imparts with phase modulation of π. After the 2D inverse discrete Fourier transform, the image has a unique shift in phase encoding direction.

Images can not only be shifted in the phase encoding direction (vertical in Figure 1) but also can be shifted in the frequency encoding direction (horizontal in Figure 1) by applying a global phase addition to A/D converter. In the mSPECS-CAIPI model, images will shift in a cyclical pattern.

Hadamard Phase Encoding: The Hadamard phase encoding technique is a well-developed volume excitation method [5]. The conventional Magnetic Resonance (MR) imaging techniques have been limited by the size of the matrix for the acquired aliased images. The Hadamard encoding method allows the increment of the size of the acquired aliased image matrix by aliasing in both frequency and phase encoding dimensions. The Hadamard matrix is given by Eq 2.

$$H_{2^n} = \begin{bmatrix} H_{2^{n-1}} & H_{2^{n-1}} \\ H_{2^{n-1}} & -H_{2^{n-1}} \end{bmatrix} = H_2 \otimes H_{2^{n-1}} \tag{2}$$

In Eq 2, ⊗ denotes the Kronecker product. The Hadamard matrix is a square and orthogonal matrix with elements of either 1 or -1. In the mSPECS-CAIPI approach technique, each excitation in time series is sequentially coordinated with a unique Hadamard encoding aliasing pattern as in Figure 2. Same as the sequential properties of imaging shifted technique, the Hadamard phase encoding aliasing pattern will cycle through along the TR dimension.

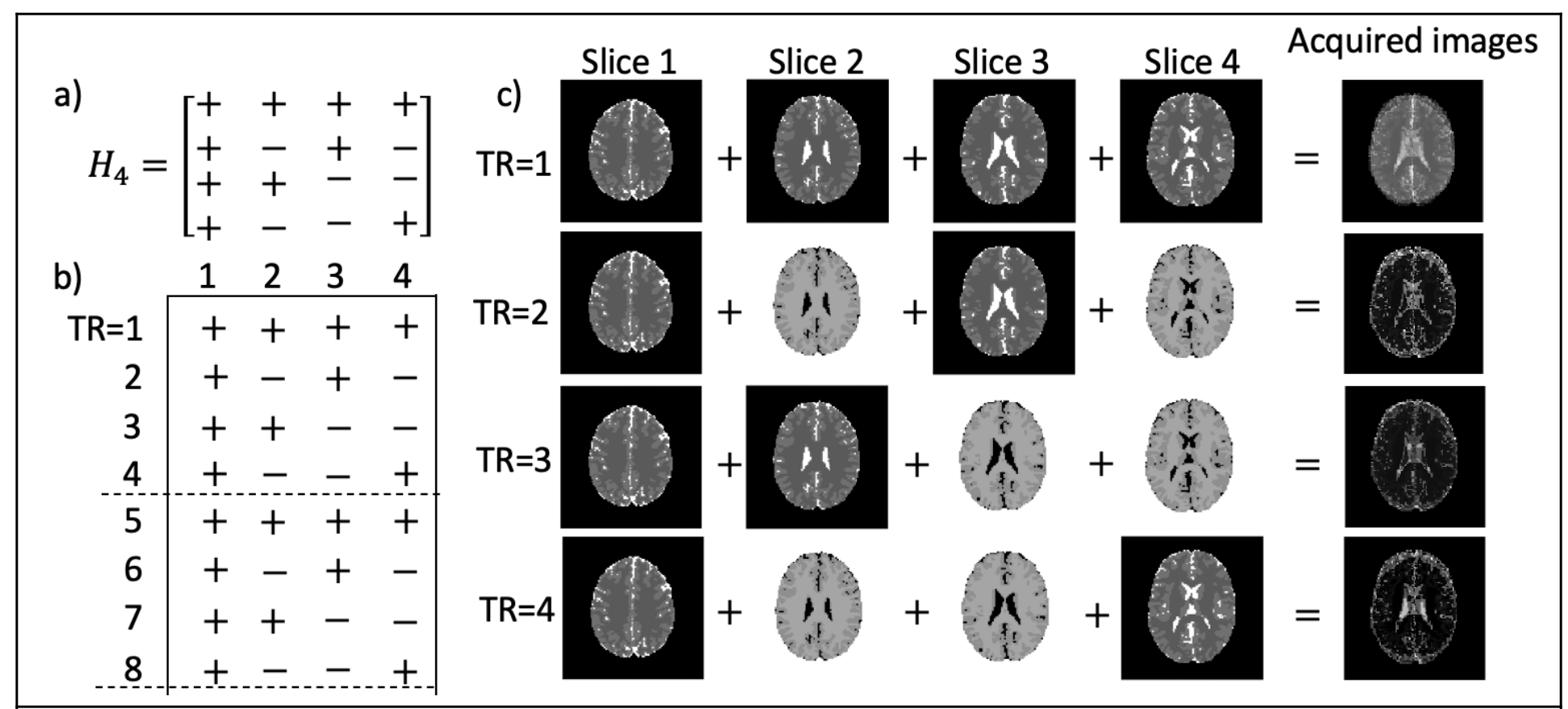

Figure 2: The diagram of the Hadamard phase encoding aliasing process of 4 slices. Each excitation will coordinate with a unique Hadamard coefficient. The Hadamard aliasing coefficients will have a cycle pattern along the excitation.

Bootstrap Sampling and Artificial Aliasing of Calibration Images: In the mSPECS-CAIPI model, for each excitation, N_s bootstrap sampled coil slices images will be randomly chosen from the fully sampled calibration reference images. The mean calibration images will be calculated for each slice. Then the mean calibration images will be artificially aliased, and this process will be repeated for each TR. According to the mSPECS-CAIPI model, the process of the acquired images and the artificial aliasing calibration images can be described as Eq 3, with X_A is the acquired aliasing matrix and C_A is the artificial aliasing matrix. The measurement error is normally distributed

$$y = \begin{bmatrix} a \\ v \end{bmatrix} = \begin{bmatrix} X_A\beta \\ C_A\mu \end{bmatrix} + \begin{bmatrix} \varepsilon \\ C\eta \end{bmatrix}, \tag{3}$$

$$(X_A)_{\gamma,\delta} = \left[H_{\delta,1}R_{\gamma,1}\begin{pmatrix} S_{1,1} \\ \vdots \\ S_{N_c,1} \end{pmatrix}, \ldots, H_{\delta,N_s}R_{\gamma,N_s}\begin{pmatrix} S_{1,N_s} \\ \vdots \\ S_{N_c,N_s} \end{pmatrix} \right], X_A = \begin{bmatrix} (X_A)_1 \\ \vdots \\ (X_A)_{N_\alpha} \end{bmatrix}, \tag{4}$$

$$(C_A)_{\gamma,\delta} = \left[\overline{H_{\delta,1}R_{\gamma,1}}\begin{pmatrix} S_{1,1} \\ \vdots \\ S_{N_c,1} \end{pmatrix}, \ldots, \overline{H_{\delta,N_s}R_{\gamma,N_s}}\begin{pmatrix} S_{1,N_s} \\ \vdots \\ S_{N_c,N_s} \end{pmatrix} \right], C_A = \begin{bmatrix} (C_A)_1 \\ \vdots \\ (C_A)_{N_\alpha} \end{bmatrix}. \tag{5}$$

The least squares estimation is joined with the mSPECS-CAIPI method, which leads Eq 3 to Eq 6:

$$\hat{\beta} = (X_A'X_A + C_A'C_A)^{-1}(X_A'a + C_A'v), \tag{6}$$

$C_A'C_A$ works as the regularizer for matrix inverse in Eq 6. The covariance for the acquired aliasing measurement error is $cov(\varepsilon) = \sigma^2 I_{2N_cN_\alpha}$, and the covariance for the artificial aliasing measurement error is $cov(C\eta) = \sigma^2 I_{2N_SN_c(N_SN_r-1)}$. With the support of the bootstrap sampling technique, the variation of the artificial aliasing calibration images will retain, thus $\tau^2 = \sigma^2$, and the covariance of $\hat{\beta}$ is given by Eq 7:

$$cov(\hat{\beta}) = \sigma^2(X_A'X_A + C_A'C_A)^{-1}. \tag{7}$$

Therefore, the correlation induced by the un-aliasing process is minimized, and the inter-slice signal leakage artifacts are eliminated.

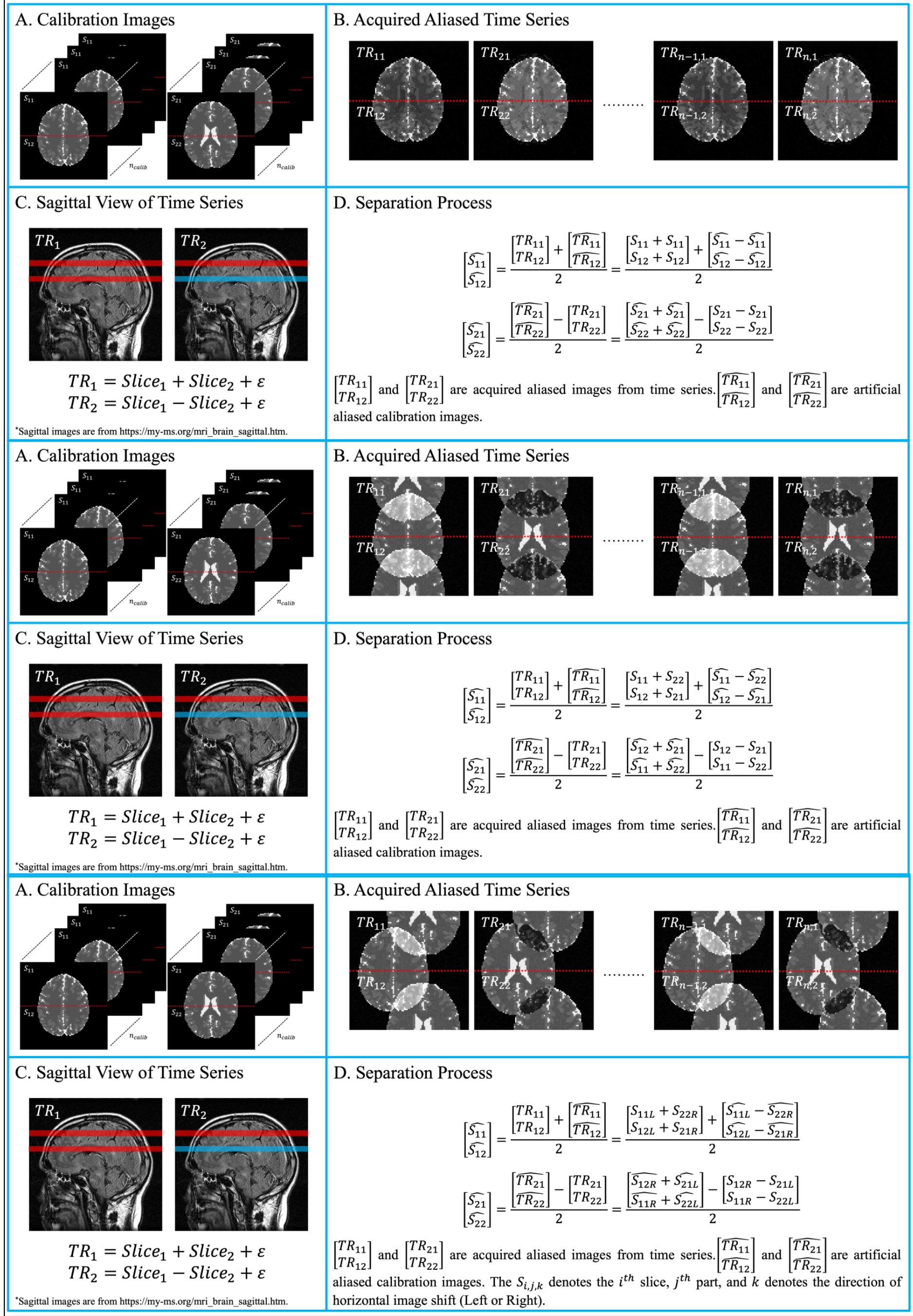

Figure 3: The mSPECS image reconstruction method (first two rows). The mSPECS-CAIPIRINHA image reconstruction method (middle two rows). The mSPECS-CAIPIVAT image reconstruction method (last two rows.). A are calibration images. B are simulated acquired aliased time series images. C are sagittal view of the time series images. D are separation process for each method.

RESULTS

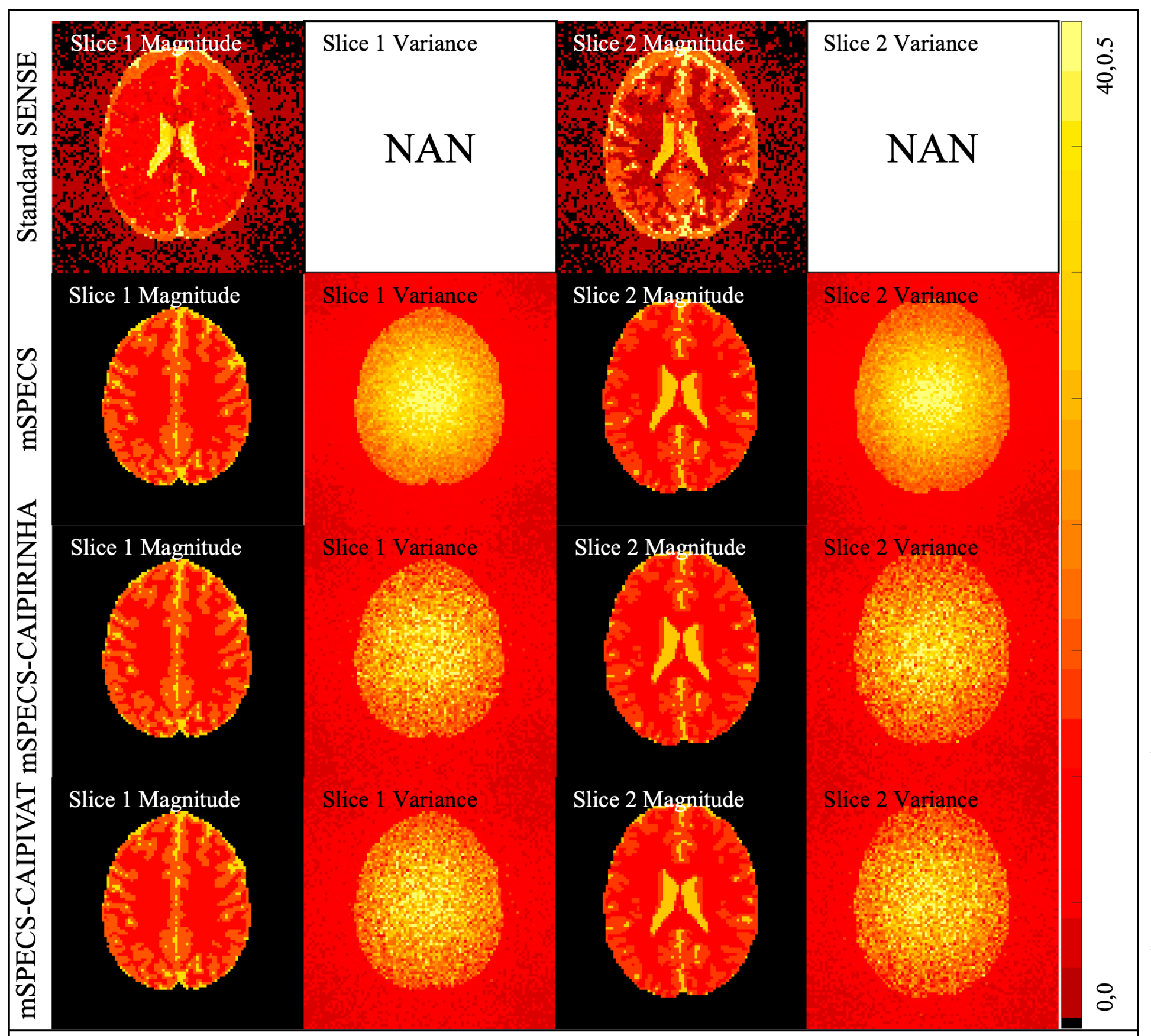

Figure 4: The mean magnitude images and variance of magnitude for standard SENSE, mSPECS, mSPECS-CAIPIRINHA, and mSPECS-CAIPIVAT with through-plane acceleration $A = 2$.

The mSPECS-CAIPIRINHA and the mSPECS-CAIPIVAT image reconstruction model are applied to simulated data and compared with the plain mSPECS method (without imaging shifts) and the standard SENSE method. The four methods are first applied to non-task simulated activation data. Experiments with different through-plane acceleration factors will be investigated. Phantom images will be put into different packets and aliased according to the Hadamard coefficients and imaging shifts patterns for each TR. The relationship of the number of packet and through-plane acceleration factor is $N_s = N_{pack}A$, and N_s is the total number of images. The in-plane acceleration will not be included into the simulated data. The SNR ratio is calculated by $SNR = \beta_0/\sigma$, β_0 is the baseline voxel value and σ is the standard deviation of the noise. The *g*-factor is calculated according to Eq. 1. Since no in-plane acceleration factor is included in the data, $R = 1$. Figure 4 shows the SNR ratio map and the *g*-factor map for three models and the SNR value for a random voxel inside the brain under different acceleration factor circumstances. Three models are applied to the task simulated data with 15 task and 15 non-task images alternated acquired. In Figure 5, the contrast-to-noise ratio (CNR) is calculated by $CNR = \beta_1/\sigma$, β_1 is the task activation signal, and σ is the standard deviation of the noise. The statistical task activation is calculated according to the [6] technique.

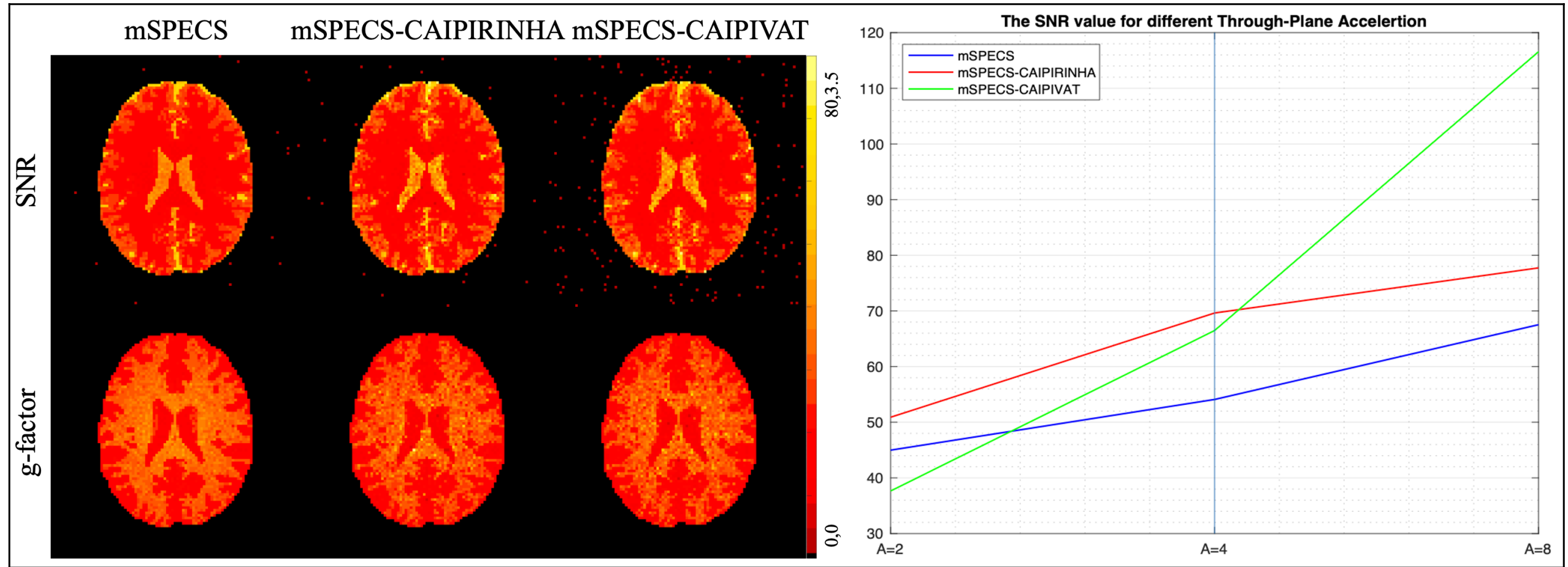

Figure 5: The SNR ratio and g-factor maps for mSPECS, mSPECS-CAIPIRINHA and mSPECS-CAIPIVAT models with through-plane acceleration $A = 2$ (left). The SNR value for a random voxel with different through-plane acceleration $A = 2$, $A = 4$, and $A = 8$ (right).

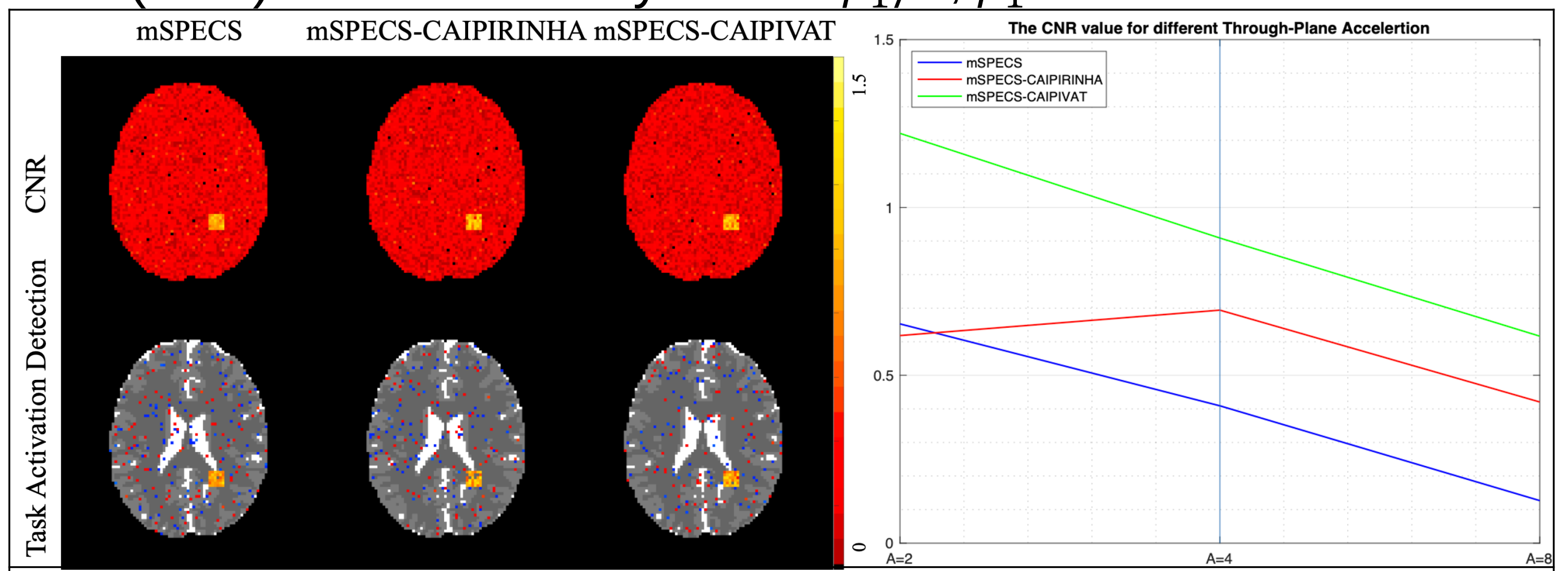

Figure 5: The CNR ratio and task activation detection maps for mSPECS, mSPECS-CAIPIRINHA and mSPECS-CAIPIVAT models with through-plane acceleration $A = 2$ (left). The CNR for a random voxel inside the task block for through-plane $A = 2$, $A = 4$, and $A = 8$ (right).

REFERENCES

(1) Pruessmann KP et al. *SENSE: Sensitivity Encoding for fast MRI*. MRM 42:952-962, 1999.
(2) Griswold MA et al. *Generalized autocalibrating partially parallel acquisition (GRAPPA).* Magn Reson Med, 47:1202-1210, 2002.
(3) Breuer FA et al. *Controlled aliasing in parallel imaging results in higher acceleration (CAIPIRINHA) for multi-slice imaging*. Magn Reson Med 2005 Mar;53(3):684-91.
(4) Kim Min-Oh et al. *MultiSlice CAIPIRINHA Using View Angle Tilting Technique (CAIPIVAT*). Tomography. 2016 Mar;2(1):43-48.
(5) Souza SP et al. *SIMA-simultaneous multislice acquisition of MR images by Hadamard-encoded excitation.* J Comput Assist Tomogr 1988;12;1026-1030.
(6) Rowe DB et al. *A complex way to compute fMRI activation*. Neuroimage. 2004 Nov;23(3):1078-92.