MULTIBAND DYNAMIC COMPRESSED SENSING

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ABSTRACT

The combination of the PI with CS reconstruction has been an important research topic in MR community due to its potential for further acceleration in MR acquisition. In particular, the application to the 3D volumetric imaging has great potential due to the introduction of additional dimension along slice direction. In this work, we propose a combined approach of dynamic compressed sensing (CS) and parallel imaging (PI) for dynamic simultaneous multislice (SMS) imaging using multi-band RF pulses. The proposed algorithm is tested to dynamic contrast-enhanced angiography to observe brain tissue dynamics. SMS image of slice-direction acceleration factor of 2,4 and 8 with in-plane acceleration of 2 are reconstructed by the proposed multi-band dynamic CS algorithm. The reconstructed results show that a proper combination of CS and parallel imaging can effectively suppress noise propagation and provide improved spatio-temporal resolution under high acceleration factor.

Index Terms— multi-band RF pulse, SMS imaging, dynamic MRI, DCE-MRI, parallel imaging, compressed sensing, slice-GRAPPA

1. INTRODUCTION

MRI is a slow imaging modality due to its principle of signal generation, so there have been constant demands for fast data acquisition. There are several approaches to enable accelerated acquisition in MRI. For example, strong gradient and the control of the number of echo train length can be used for the accelerated acquisition. A lot of fast pulse sequences have been devoloped. On the other hand, a sophisticated algorithms can be used to reconstruct the image from the undersampled data. For example, partly acquired k-space data are reconstructed using PI technique with different coil-sensitivity information from several receiver coils[1]. CS has been another main stream of research to enable accelerated acquisition by exploiting the spatio-temporal redundancies [2].

3D volumetric encoding has become an important option for fast acquisition. If data are acquired as a 3D volume, SNR increases and the total time becomes shorter than the multiple 2D image acquisition. Volume imaging rapidly scans the 3D k-space than imaging multiple single slices. However, there is a limitation in using 3D encoding since slowly varying k-space dimensions are subject to susceptibility distortion. Thus the use of PI is required in 3D volumetric imaging, especially in ultra-high field MRI.

Another option for accelerated data acquisition is the simultaneous multislice (SMS) imaging using multiband RF pulses [3]. As can be inferred from its name, in SMS, multiple slices are simultaneously excited and acquired in one slice as overlapped form. SMS imaging can be applied to various area such as fMRI and diffusion imaging with EPI sequence.

In perspective of image reconstruction, the diversities of spatial sensitivity information from multiple coils along slice direction are utilized for slice separations in SMS imaging. More specifically, to resolve the slice directional aliasing, a variety of parallel imaging algorithms are used for SMS reconstruction algorithms[3, 4, 5]. However, in spite of extensive research activities, the combination of the SMS technique with dynamic compressed sensing is rare[6].

In this paper, a novel multiband dynamic compressed sensing algorithm is developed by combining SMS imaging with dynamic compressed sensing. In this scheme, not only the multiband RF pulse is used, but also phase encoding directions are skipped along spatio-temporal direction. Therefore, there exists two types of aliasing artifacts: one from slice direction and the other from spatio-temporal direction. Therefore, the main goal is to investigate how to resolve such combined artifact by exploiting spatio-temporal redundancies and the coil sensitivity diversity. Here, we reveal that the parallel imaging and CS should be applied in distinct order for SMS scheme.

2. THEORY

2.1. Parallel imaging techniques for SMS imaging

In this subsection, several MB reconstruction algorithms are reviewed. We can write the inverse problem in SMS as following:

$$S_{c1}\rho_1 + S_{c2}\rho_2 + \cdots + S_{cz}\rho_z + \cdots + S_{cZ}\rho_Z = \bar{\rho}_c, \quad (1)$$

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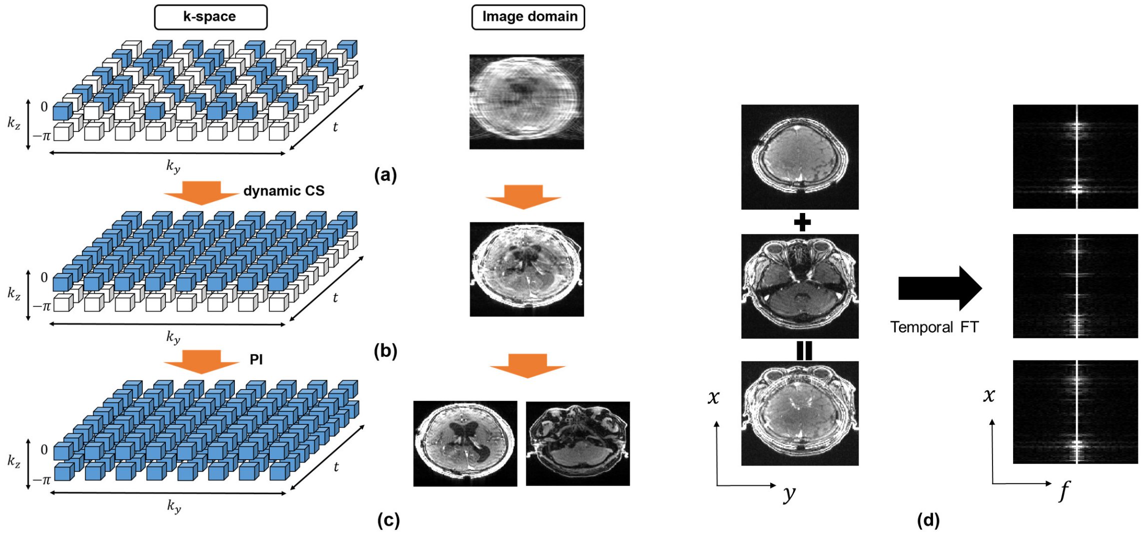

Fig. 1: (a) Sampling pattern in k-space with in-plane reduction factor of 2 and MB factor of 2. (b) CS is applied to fill the randomly skipped k-space samples. (c) PI separates the individual slices. (d) Time series of slice directional alias image can be sparsely represented with temporal Fourier transform.

where S_{cz} is the sensitivity of the c-th coil at slice z, and ρ_z is the signal from slice z, and $\bar{\rho}_c$ is the SMS signal acquired at the c-th coil. This pixel-wise equation resembles SENSE algorithm and all the pixel values from all coils can be written similarly, arriving at the following matrix-vector equation :

$$\begin{bmatrix} S_{1,1} & S_{1,2} & \cdots & S_{1,Z} \\ S_{2,1} & S_{2,2} & & S_{2,Z} \\ S_{3,1} & S_{3,2} & \cdots & S_{3,Z} \\ \vdots & \vdots & & \vdots \\ S_{C,1} & S_{C,2} & \cdots & S_{C,Z} \end{bmatrix} \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \vdots \\ \rho_Z \end{bmatrix} = \begin{bmatrix} \bar{\rho}_1 \\ \bar{\rho}_2 \\ \bar{\rho}_3 \\ \vdots \\ \bar{\rho}_C \end{bmatrix}. \quad (2)$$

Then, by a simple matrix inversion each pixel value at coils is unaliased. One of the limitation of the SENSE type SMS algorithm is the difficulty of obtaining sensitivity maps. Accordingly, other MB reconstruction techniques have been proposed. One of them was SENSE/GRAPPA proposed by Blaimer et al.[4]. To implement SENSE/GRAPPA, image slices are relocated as

$$\rho(x,y,z_1) \rightarrow \rho'(x,y), \quad (3)$$
$$\rho(x,y,z_2) \rightarrow \rho'(x,y+N_y), \quad (4)$$

where ρ' is a extended 2D matrix from 3D multislice image and N_y is a PE dimension. Its reconstruction algorithm is represented as

$$\hat{v}_j(k_x, \hat{k}_y - m\Delta\hat{k}_y) = \sum_{c=1}^{C} \sum_{b_x=-B_x}^{B_x} \sum_{b_y=-B_y}^{B_y} w_{j,m,c}^{b_x,b_y} \hat{v}_c$$
$$(k_x - b_x\Delta k_x, \hat{k}_y - b_y N_{\text{slice}} \Delta k_y), \quad (5)$$

where $\hat{v}_j$ denotes the k-space measurement at the j-th coil, $\hat{k}_y$ is augmented k-space of PE lines and N_{slice} denotes the number of simultaneously acquired slices. $w_{j,m,c}^{b_x,b_y}$ is the GRAPPA weight at position (b_x, b_y) for the c-th coil to estimate the missing data of the j-th coil at a position $m\Delta\hat{k}_y$ away.

Recently, Setsompop et al. suggested GRAPPA type algorithm, which is call slice-GRAPPA as an alternative to SENSE/GRAPPA[5]. The slice-GRAPPA is often used to reconstruct multiple slices from an aliased image. Here, a z-slice is reconstruction using the following formulation:

$$v_{j,z}(k_x, k_y) = \sum_{c=1}^{C} \sum_{b_x=-B_x}^{B_x} \sum_{b_y=-B_y}^{B_y} w_{j,z,c}^{b_x,b_y} v_{c,MB} \quad (6)$$
$$(k_x - b_x\Delta k_x, k_y - b_y\Delta k_y),$$

where $v_{j,z}$ denotes the estimate k-space data at the j-th coil and z-slice, and $v_{c,MB}$ is the aliased k-space data at c-th coil.

2.2. Proposed algorithm

In this work, time series of brain data is reconstructed. To use dynamic CS for acceleration, phase encoding lines are randomly downsampled while retaining multi-band RF acquisition as shown in Fig. 1. Accordingly, this results in two types of aliasing: one along spatio-temporal direction and the other for slice direction. To resolve the aliasing artifacts, we could combine the PI algorithm to resolve the aliasing in the slice direction and dynamic CS algorithm for spatio-temporal aliasing[2]. The main issue is, however, how to combine these two.

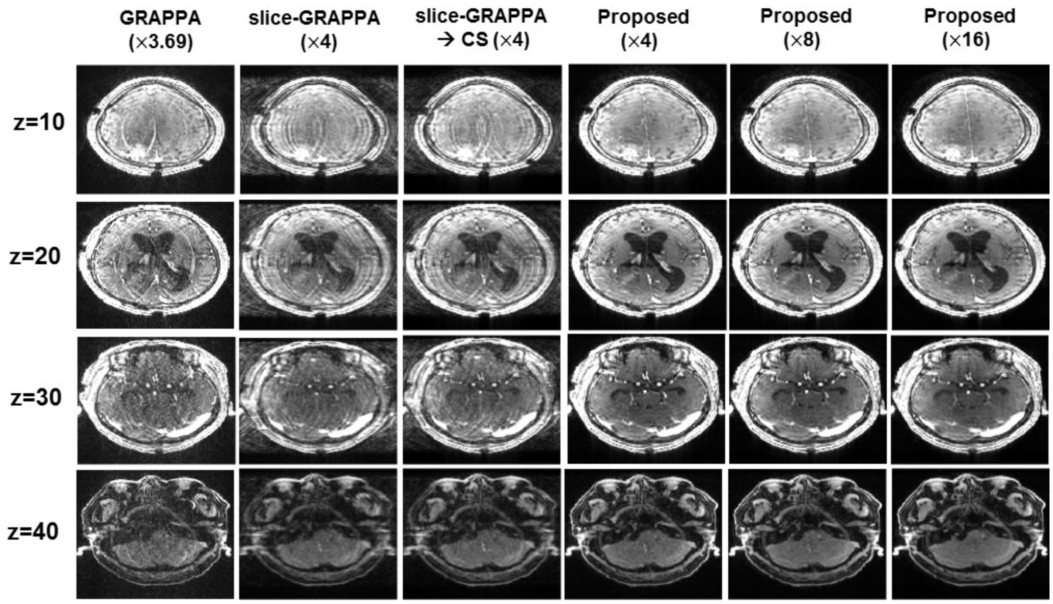

Fig. 2: Reconstruction results using various algorithms at various downsampling factors. MB factor is 2 and 10th and 30th, and 20th and 40th slices were simultaneously processed.

We found that the resolving spatio-temporal aliasing should be done before we attempt to address the slice aliasing. More specifically, we firstly reconstructed the image using k-t FOCUSS algorithm [2]. k-t FOCUSS finds the sparse solution of the following l_1 minimization problem

$$\hat{\boldsymbol{\rho}} = \arg\min_{\mathbf{x}} ||\mathbf{y} - F\boldsymbol{\rho}||_2^2 + \lambda||\boldsymbol{\rho}||_1 \tag{7}$$

using a simple iteratively reweighted least-squares problem:

$$\hat{\mathbf{q}}_i = \arg\min_{\mathbf{x}} ||\mathbf{y} - F\mathbf{W}_i\mathbf{q}_i||_2^2 + \lambda||\mathbf{q}_i||_2^2 \quad \text{subject to} \quad \boldsymbol{\rho}_i = \mathbf{W}_i\mathbf{q}_i. \tag{8}$$

Here, $\boldsymbol{\rho}$ is sparse $x-f$ spectrum and $\mathbf{y}, F$ represent k-space measurement and Fourier transform, respectively. $\mathbf{W}$ is a weighting matrix updated at each iteration.

Recall that brain imaging data can be sparsely represented when the data is acquired as a time series because head is relatively motionless. Accordingly, even the overlapped slice can be easily sparsified along temporal direction since the temporal variations of most pixels in brain image series are very small. This phenomenon can be easily observed in Fig. 1 (d), where the x-f spectrum of the unaliased image and slice-directional aliased images are shown. Note that even though the slice images are aliased into one, the resulting spectrum in frequency domain is still sparse. Therefore, the dynamic compressed sensing algorithm can be used first to remove the spatio-temporal aliasing.

After aliasing along spatio-temporal dimension is resolved, only aliasing artifacts along slice direction remain. To separate the individual slices from the overlapped slice, we used slice-GRAPPA algorithm[5]. The slice-GRAPPA kernel was estimated using fully sampled pre-scan data of each slice and the first frame of the spatio-temporally reconstructed overlapped data. Then, the estimated kernel was used for slice separation for all sequential time frames.

Fig. 1 (a)-(c) show the k-space at each reconstruction step and the corresponding images. Randomly sampled k-space data are filled using CS algorithm ((a)→(b)), and the filled k-spaces are separated using slice-GRAPPA((b)→(c)).

3. RESULTS

3D DCE data was acquired using TWIST sequence[7] on a 32 coil Siemens 3T Verio scanner at Seoul National University Hospital, Korea. Acquisition parameters are as follows : 192x252 matrix size, 40 partition encoding lines, TR/TE 2.81/1.04 ms, slice thickness 3 mm, 32 channels and 60 time frames. Informed consent was obtained from the subject for data acquisition. This data is considered as fully sampled data, and retrospective undersampling was conducted for both slice and spatio-temporal dimensions. The slices separated equidistantly were selected as a set of SMS image and the proposed algorithm was conducted to the set of individual slices.

Downsampling rate along slice dimension was 2 and in-plane downsampling factor were 2,4, and 8 (total of 4,8, and 16). Fig. 2 shows the reconstruction results using various methods. Here, for standard GRAPPA, each slice was downsampled with sampling rate of 6 and 32 ACS lines (total

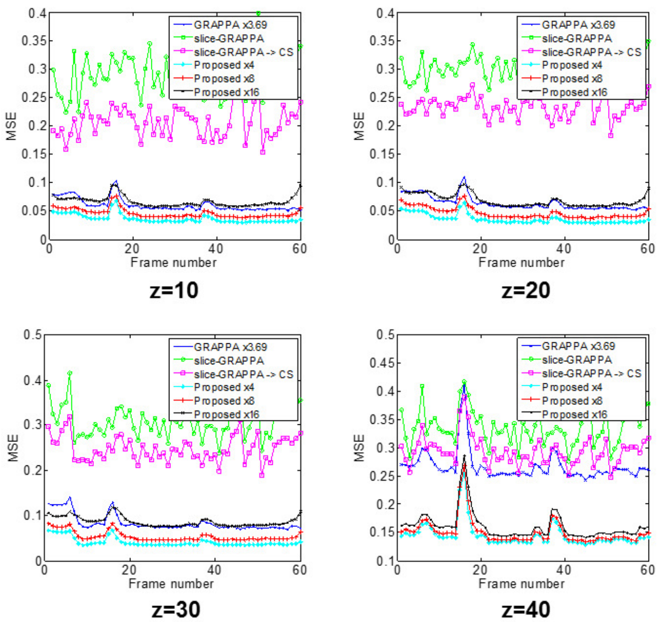

Fig. 3: MSE plots of compared algorithms in Fig. 2.

downsampling rate 3.69). This was used as reference. We confirmed that the proposed algorithm shows better result than normal GRAPPA algorithm for dynamic imaging. Even in the higher acceleration such as 8 and 16, the proposed algorithm shows much improved performance. Also, we observed that reconstruction order is critical for reconstruction quality. Specifically, when slice-GRAPPA is applied prior to CS, aliasing artifacts were not removed as shown in the second column of Fig. 2. This is because removing spatio-temporal aliasing is critical to retain the performance of slice GRAPPA. The MSE plots in Fig. 3 also confirmed that the proposed algorithm produced much reduced MSE values at all time frames.

4. DISCUSSION AND CONCLUION

In this work, we employ the slice-GRAPPA for separation of the superimposed slices. The difference between the use of the slice-GRAPPA in this work and those in [5], is that slice-GRAPPA is used for separation of individual slices from dynamically reconstructed image in the proposed work, while in [5], it was used as a preparation for conventional GRAPPA. Specifically, when there are slice- and in-plane undersampling together, slice-direction is solved first using slice-GRAPPA and then conventional GRAPPA is conducted to unalias the in-plane aliasing in [5].

However, in the proposed work, aliasing along spatio-temporal dimension is solved using dynamic CS algorithm first, and then the slice aliasing is solved. The reason for this is that in dynamic imaging even slice aliased image can be sparsified in x-f domain due to the temporal redundancy.

In summary, a novel reconstruction algorithm using compressed sensing and parallel imaging combination for dynamic simultaneous multislice imaging application was proposed. We investigated how to combine the multi-band imaging and compressed sensing reconstruction to further accelerate the acquisition. Experimental results showed that the proposed method was effective for denoising and improved spatio-temporal resolution compared to the existing methods.

5. REFERENCES

[1] K. P. Pruessmann, M. Weigher, M. B. Scheidegger, and P. Boesiger, "SENSE: Sensitivity encoding for fast MRI," *Magn. Reson. Med*, vol. 42, no. 5, pp. 952–962, 1999.

[2] H. Jung, K. Sung, K.S. Nayak, E.Y. Kim, and J.C. Ye, "k-t FOCUSS: A general compressed sensing framework for high resolution dynamic MRI," *Magnetic Resonance in Medicine*, vol. 61, no. 1, pp. 103–116, 2009.

[3] David J Larkman, Joseph V Hajnal, Amy H Herlihy, Glyn A Coutts, Ian R Young, and Gösta Ehnholm, "Use of multicoil arrays for separation of signal from multiple slices simultaneously excited," *Journal of Magnetic Resonance Imaging*, vol. 13, no. 2, pp. 313–317, 2001.

[4] Martin Blaimer, Felix A Breuer, Nicole Seiberlich, Matthias F Mueller, Robin M Heidemann, Vladimir Jellus, Graham Wiggins, Lawrence L Wald, Mark A Griswold, and Peter M Jakob, "Accelerated volumetric MRI with a SENSE/GRAPPA combination," *Journal of Magnetic Resonance Imaging*, vol. 24, no. 2, pp. 444–450, 2006.

[5] Kawin Setsompop, Borjan A Gagoski, Jonathan R Polimeni, Thomas Witzel, Van J Wedeen, and Lawrence L Wald, "Blipped-controlled aliasing in parallel imaging for simultaneous multislice echo planar imaging with reduced g-factor penalty," *Magnetic Resonance in Medicine*, vol. 67, no. 5, pp. 1210–1224, 2012.

[6] Berkin Bilgic, Kawin Setsompop, Julien Cohen-Adad, Anastasia Yendiki, Lawrence L Wald, and Elfar Adalsteinsson, "Accelerated diffusion spectrum imaging with compressed sensing using adaptive dictionaries," *Magnetic Resonance in Medicine*, vol. 68, no. 6, pp. 1747–1754, 2012.

[7] Gerhard Laub and Raldall Kroeker, "syngo TWIST for dynamic time-resolved MR angiography," *Magnetom Flash*, vol. 3, pp. 92–95, 2006.