

Simultaneous Image and K-space Domain Aliasing for Accelerating Dynamic MRI Scans

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Introduction:

A new MRI acceleration technique, referred to as RATE, which relies on a new concept of k-space aliasing, has recently been introduced [1]. RATE uses tailored excitation modules consisting of RF pulses and gradients to deliberately overlap distinct k-space points. This accelerates a scan as all k-space points in a time frame can now be sampled in a time span shorter than that of a full acquisition. The RF excitation pulses are used to tag the overlapped k-space points that are then resolved through a Fourier transformation in time. In this work, techniques to combine RATE with Parallel Imaging (PMRI) and Compressed Sensing (CS) methods have been demonstrated. When used in this manner, the total acceleration will be $A_{RATE} * A_{PMRI/CS}$ where $A_{PMRI/CS}$ is the acceleration due to the PMRI/CS process. An interesting observation on such a combination is that data will now be sub-sampled in both the image and k-space domains simultaneously, resulting in the multiplicative increase in acceleration. The additional acceleration can be used to either eliminate aliasing artifacts or track signals with large temporal bandwidths.

Theory:

Summary of RATE: A tailored signal excitation module designed for an acceleration factor of 2, is given in Fig.1. The RF pulses $P_1(t)$ and $P_2(t)$ are slice selective, the flip angles of both the pulses are equal to θ . $P_1(t)$ and $P_2(t)$ excite the same slice and are accompanied by gradient blips with amplitudes G_{pe1} and G_{pe2} in the primary phase encoding direction. The resulting signal is $S_l(t, n_{tf}) = \iint \rho_l(x, y) \cdot O(x, y) \{A_1 e^{-jk_1 y + \phi_1 n_{tf}} + A_2 e^{-jk_2 y + \phi_2 n_{tf}}\} e^{-jk_x x} dx dy$. Here $k_1 = \gamma(G_{pe1} + G_{pe2})t_p$ and $k_2 = \gamma G_{pe2} t_p$, $\rho_l(x, y)$ is the complex sensitivity profile of l^{th} receive coil and $O(x, y)$ is 2D slice profile, A_1, A_2 is determined by the flip angle of all/some RF pulses; ϕ_1, ϕ_2 are the initial phase of RF pulses in aliasing module, and n_{tf} is the time frame number. RATE reconstruction involves Fourier transformation of the acquired signal $S_l(t, n_{tf})$ in time that places temporal spectra of k_1 and k_2 determined by ϕ_1 and ϕ_2 on the temporal frequency axis. These can be separated using Fermi filter as shown in Fig.1b.

Combination of RATE with PMRI: In order to combine RATE with PMRI, the gradient blips G_{pe1} and G_{pe2} in the RATE signal excitation module are varied in such a manner that undersampled aliased k-space data is acquired. The acquired data is first processed with the RATE reconstruction method to unalias k-space and generate the conventional undersampled k-space dataset as would have been acquired using PMRI alone. As shown in Fig.2, the RATE reconstruction output is processed by any appropriate PMRI method to generate the final k-space output.

Combination of RATE with CS: In a similar manner, CS is combined with RATE by first acquiring randomly undersampled aliased k-space similar to sampling pattern suggested in [2]. The RATE reconstruction is applied on the acquired data to reconstruct randomly undersampled k-space as would have been acquired using CS directly. CS reconstruction with l_1 minimization and TV penalty is now applied on data from each time frame to reconstruct full k-space.

Materials and Methods:

All experiments were conducted on a Siemens 1.5T scanner. A cardiac cine feasibility study was conducted using a FGRE sequence with FOV: 300*300mm, 256 phase encodes, TR=6ms, 16 cardiac phases, segment size of 10 with an excitation module designed for $A_{RATE} = 2$. With a module designed for $A_{RATE} = 3$, the altered scan parameters were TR=7ms, segment size=6 and 23 cardiac phases were collected. A total of 128 phase encodes were acquired with RATE for $A_{RATE} = 2$. For demonstrating CS-RATE, 64 phase encodes were randomly sampled from the RATE accelerated dataset. For demonstrating PMRI-RATE, alternate phase encodes were discarded from the accelerated RATE dataset. A similar process was repeated for demonstrating the same with $A_{RATE} = 3$. We utilized the GRAPPA method for PMRI and some loss in acceleration occurred due to the acquisition of additional ACS lines.

Results: Fig.3 shows the reconstructed images for RATE and its different combinations with CS/PMRI. Additionally, simulations results using fully sampled datasets confirmed the fidelity of temporal information within an error range of 0.0 to 0.15. Figures 4a and 4b show the temporal curves for the regions of interest pointed to by the white arrows in Fig.3 for the accelerated datasets. for CS-RATE combination, dashed line for PMRI-RATE combination and solid line is from the dataset accelerated using only RATE.

Discussion: RATE utilizes multiple RF excitation pulses to generate multiple signal pathways that are gradient encoded with different phase encoding gradients such that the acquired k-space data is aliased. Therefore, while there are some similarities with UNFOLD [3] as far as the temporal filtering step is concerned, the RATE concept is completely different. As a result, when combined with PMRI/CS, the resulting acceleration benefits are far superior to what has previously been demonstrated with UNFOLD [4]. Future work will focus on combining RATE with both PMRI and CS methods simultaneously for 3D imaging applications.

References:

[1] Arunachalam et al. Submitted. ISMRM 2012. [2] Lustig et al. 58:1182, 2007. [3] Madore et al. MRM 48:493, 2002. [4] Kellman et al. MRM 45:846, 2001.

Acknowledgements: The authors thank Michael Lustig for inputs in using his SparseMRI code.

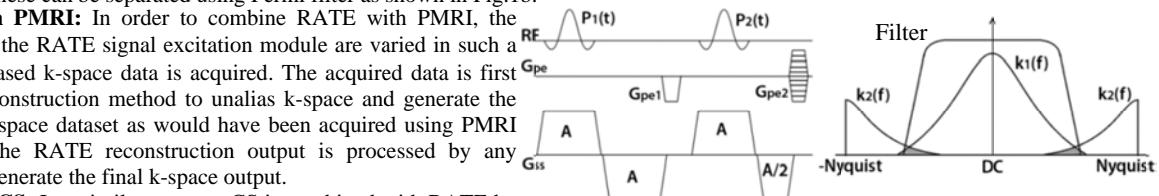


Figure 1: (a) Excitation module for $A_{RATE} = 2$. (b) $k_1(f)$ and $k_2(f)$; the Fourier spectrum of $k_1(t)$ and $k_2(t)$ respectively, separated using a Fermi

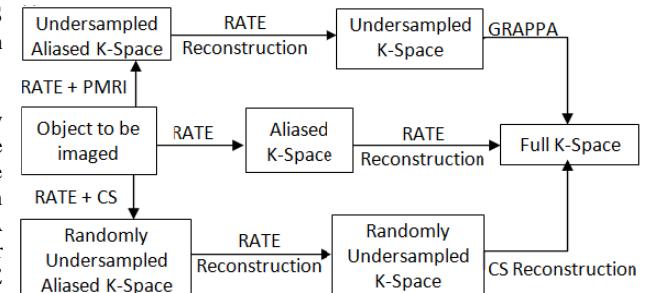


Figure 2: Block diagram outlines the reconstruction steps for RATE alone and in combination with PMRI and CS

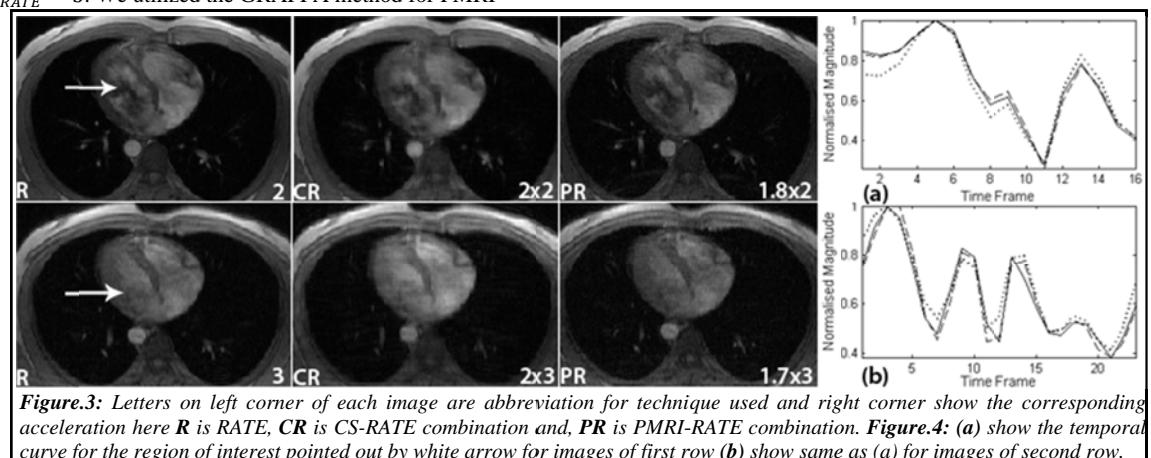


Figure 3: Letters on left corner of each image are abbreviation for technique used and right corner show the corresponding acceleration here R is RATE, CR is CS-RATE combination and, PR is PMRI-RATE combination. Figure 4: (a) show the temporal curve for the region of interest pointed out by white arrow for images of first row (b) show same as (a) for images of second row.