Accelerated Simultaneous Multi-slice Cardiac Cine Imaging Using a Combination of CAIPIRINHA and Compressed Sensing

D. Stäb[1], T. Wech[1], C. Ritter[1], D. Hahn[1], and H. Köstler[1]
[1]Institute of Radiology, University of Wuerzburg, Wuerzburg, Bavaria, Germany

Introduction:

Compressed Sensing (CS) techniques (1-3) have shown their potential to significantly accelerate data acquisition. Non-linear optimization algorithms utilizing prior knowledge allow exact reconstructions of highly undersampled data. Recently, various approaches (4-5), incorporating Parallel Imaging (PPA) came up with promising results and further increased acceleration factors (R).
In terms of multi-slice imaging, the simultaneous multi-slice imaging technique CAIPIRINHA (6) has proven to be a very effective alternative to conventional parallel imaging. Several slices are excited simultaneously, shifted with respect to each other in the FOV (coherent aliasing), and reconstructed using parallel imaging techniques. In contrast to the conventional in-plane parallel imaging approaches, the image quality is mainly conserved, as the scan time per image is maintained and the reconstruction provides low geometry factors.
In this work a serial two-step combination of CAIPIRINHA with Compressed Sensing is proposed. First results, showing the capability to perform highly accelerated simultaneous multi-slice imaging are presented.

Material and Methods

The basic idea of this approach is to excite several slices at the same time and undersample k-space in random incoherent fashion. For image reconstruction, in a first step, Compressed Sensing is applied to eliminate the incoherent artifacts introduced by random k-space undersampling. The remaining coherent aliasing artifacts, generated by simultaneously exciting several slices, are removed in a second step, using parallel imaging (fig. 1).

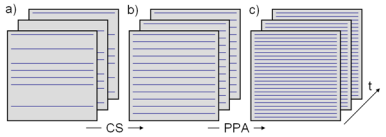

Fig. 1: *Basic reconstruction scheme, showing k-space of 3 time frames* ***(a)*** *after the measurement,* ***(b)*** *after the CS reconstruction and* ***(c)*** *after the final PPA reconstruction.*

In-vivo cardiac cine imaging experiments were performed on a 1.5T MAGNETOM Avanto system (Siemens Healthcare, Erlangen, Germany) using a 32 channel cardiac array (Rapid Biomedical, Rimpar, Germany) for signal reception. A segmented cine TrueFISP sequence (FOV: 320 x 270 mm^2, matrix: 256 x 176, slice thickness: 8 mm, slice distance: 20 mm, TR: 3.8 ms, TE: 1.92 ms, flip angle: 70°, 33 frames/s) commonly used in clinical routine was equipped with CAIPIRINHA according to (7). Two slices were excited at the same time and shifted by a ½ FOV with respect to each other by choosing the constant rf phase increments between succeeding multi-band excitation pulses to be +90° and -90° in the first and second slice respectively.
Incoherent undersampling was performed retrospectively according to a potential measurement scheme. Each time frame was individually undersampled (R = 2.1), applying a random sampling with Gaussian density distribution along the phase encoding direction.
For each coil, sparse dynamic difference images x were calculated by subtracting the temporal average of the undersampled dataset from each single time frame. Signal recovery was performed using the L_1 minimization (8)

$$(1) \qquad \min_{x}\left\{\left\|x\right\|_1 + \mu \cdot \left\|Ax - y\right\|_2^2\right\},$$

where A is a sparsifying fourier transform of x according to the applied undersampling scheme and y denotes the acquired data. μ was chosen to be 3.5 10^{-2}. The second reconstruction step was performed using GRAPPA (9) (R=3) in combination with a low resolution reference scan for calibration.
In order to assess the quality of the image reconstruction, additional noise scans were performed and g-factor maps were calculated using a modified multiple-replica approach (10).

Results

Compressed Sensing and CAIPIRINHA accelerated cardiac cine imaging can be successfully performed in several slices simultaneously. Fig. 2 compares the GRAPPA reconstruction of the full dataset (fig. 2a) with the proposed combined reconstruction of the incoherently undersampled dataset (fig. 2b). A corresponding 10 fold enhanced difference image is displayed in fig. 2c. Only very small differences can be detected between the 2 reconstructions.
In all studies, the reconstruction separated the two simultaneously excited slices without visible reconstruction artifacts. G-factor maps revealed generally low noise enhancement inhomogeneously distributed over the subject with maxima in regions of physical motion (data not shown).

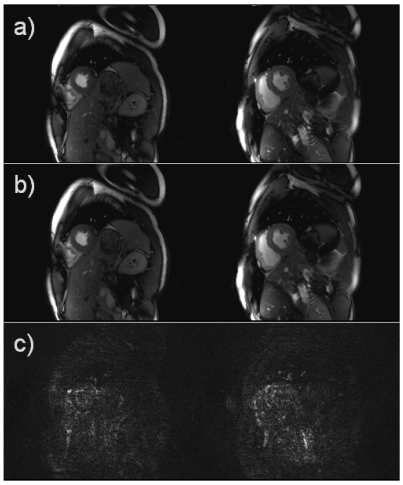

Fig. 2: *Comparison of reconstructed images of the two simultaneously excited slices. Displayed are* ***(a)*** *the conventional reconstruction of the CAIPIRINHA acquisition using GRAPPA and* ***(b)*** *the reconstruction of the incoherently undersampled CAIPIRINHA acquisition using the proposed combination of Compressed Sensing and GRAPPA.* ***(c)*** *Difference between a) and b) magnified by a factor of 10.*

Conclusions

Compressed Sensing can be successfully combined with CAIPIRINHA multi-slice imaging, resulting in an effective acceleration in both, slice and phase encoding direction. Both techniques are capable of reconstructing images with only marginal noise enhancement. Thus the image quality obtained with the combined approach is comparable to that achieved in a 4 times longer standard single-slice acquisition. The approach shows promising results and may be useful for various applications, e.g. perfusion or real-time imaging.
However, as for most Compressed Sensing approaches, the reconstruction time (15 minutes on a standalone pc) requires further reduction.

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