Cardiac Perfusion Imaging Using a Combination of CAIPIRINHA and Compressed Sensing

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Introduction

Compressed Sensing (CS) techniques have shown their potential to significantly accelerate data acquisition. Moreover, several approaches incorporating Parallel Imaging (1-2) have been presented. Considered to allow for high acceleration factors, these combinations have also been utilized in myocardial perfusion imaging (3). However, providing increased anatomical coverage without almost any losses in image quality, the simultaneous multi-slice imaging technique CAIPIRINHA (4) has proven to be a very effective technique for cardiac perfusion imaging (5). In this work, we present a serial two-step combination of CAIPIRINHA and Compressed Sensing for high resolution myocardial perfusion imaging with extended anatomic coverage. First results, as well as an analysis of systematic and statistical errors are presented.

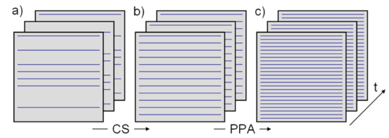

Fig. 1: *Basic reconstruction scheme, showing k-space of 3 time frames **(a)** after the measurement, **(b)** after the CS reconstruction and **(c)** after the final PPA reconstruction.*

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 reconstruction 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 (CAIPIRINHA), are removed in a second step, using parallel imaging (Fig. 1).

In-vivo cardiac perfusion measurements were performed on a 3.0T Magnetom Trio system (Siemens Healthcare, Erlangen, Germany) using a 32 channel cardiac array (Siemens Healthcare, Erlangen, Germany) for signal reception. Images were acquired using a Saturation Recovery FLASH sequence (FOV: 320 x 240 mm^2, matrix: 120 x 160, slice thickness: 8 mm, TR: 2.5 ms, TE: 1.44 ms, flip angle: 12°). Two slices (slice distance: 16mm) were acquired at the same time and shifted with respect to each other by ½ FOV by applying a constant/alternating rf phase cycle in the first/second slice. Each heart beat, two consecutive two-slice CAIPIRINHA acquisitions were performed and the pass of the contrast agent was sampled in 4 slices by 40 measurements over 40 heart beats. In order to allow for a detailed error analysis, incoherent undersampling was performed retrospectively according to a potential measurement scheme. Apart from a small central k-space region, each time frame (heart beat) was individually undersampled (R_{CS} = 2), applying a random sampling pattern with uniform density distribution along the phase encoding direction.

The Compressed Sensing reconstruction step was performed coilwise using the iterative soft thresholding algorithm (6) which is equivalent to the L_1 minimization

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

with x being the image to be reconstructed, y the acquired k-space data, A the undersampled Fourier transform of x according to the applied undersampling scheme, μ the regularization parameter, and S the sparsifying transform used to generate sparse images from the naturally non-sparse acquired perfusion images. The second reconstruction step was performed using GRAPPA (7) (R=3) in combination a reference scan.

In order to assess the quality of the Compressed Sensing reconstruction, additional noise scans were performed and a modified multiple-replica approach (8) was utilized to generate a stack of independent measurements. From these, the systematic and statistical errors were estimated by calculating the mean and standard deviation. Two different sparsifying transformations S were investigated; first: the generation of difference images by subtracting the temporal average of all time frames from each single time frame (reconstruction in xy-space), and second: a Fourier transform along the time dimension (yf-space).

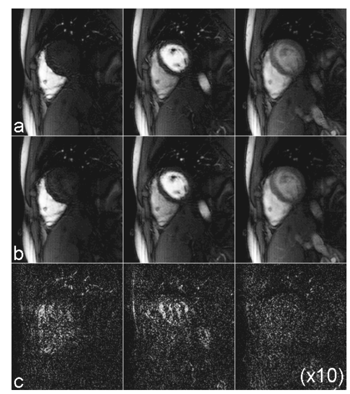

Fig. 2: *In-vivo measurement. Shown is the pass of the contrast agent through right ventricle **(left)**, left ventricle **(middle)** and myocardium **(right)** for **a:** the GRAPPA reconstruction of the fully sampled reference dataset and **b:** the combined CS GRAPPA reconstruction of the undersampled dataset. **c:** Difference between both (a) and (b) magnified by a factor of 10.*

Results

Compressed Sensing and CAIPIRINHA accelerated cardiac perfusion imaging can be successfully performed in several slices simultaneously. Fig. 2 shows image reconstructions for the reconstruction in yf-space for one slice and three different time frames in comparison to simple GRAPPA reconstructions of the reference dataset. Although the reconstructed images are free from visible reconstruction artifacts, the difference images reveal reconstruction errors. Systematic and statistical errors estimated for the compressed sensing reconstruction for one coil and time frame are displayed in Fig. 3. For both sparsifying transforms, the systematic error is about one order of magnitude higher than the statistical one and hence is responsible for the deviations in the reconstruction. Exploiting sparsity in two dimensions, the yf-reconstruction results in a lower systematical error.

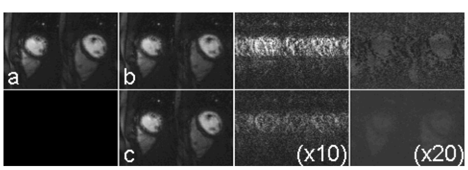

Fig. 3: *Error analysis for the CS reconstruction in one representative coil. **a:** Fourier transform of the fully sampled reference CAIPIRNHA acquisition. **b:** CS reconstruction in xy-space with corresponding systematic **(3rd column)** and statistical **(4th column)** error. **c:** Reconstruction in yf-space with errors. For better visibility, the systematic and statistical errors were magnified by a factor of 10 and 20, respectively.*

Discussion

Compressed Sensing can be combined with CAIPIRINHA multi-slice imaging, resulting in acceleration in both, slice and phase encoding direction. Applied to cardiac perfusion imaging, the approach allows the acquisition of 6-8 slices with high spatial resolution during one RR-interval. Both techniques are capable of reconstructing the images with only marginal noise enhancement. However, although revealing images with apparently high image quality, the Compressed Sensing reconstruction leads to systematic errors that might be due to a lack of sparsity in the images to be minimized. In conclusion, Compressed Sensing techniques have to be applied with care and a detailed error analysis has to be performed for each application before implementation.

References

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