<u>High resolution, functional real-time cardiac MR imaging using a combination of compressed sensing and parallel imaging</u>

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<u>Introduction:</u>
In clinical routine, segmented CINE sequences are generally used in functional cardiac magnetic resonance imaging in order to achieve high spatial and temporal resolution. Drawbacks of these methods are the need of ECG-triggering and therefore a sine rhythm on the one hand and the necessity of a breath-hold of up to 15s on the other. The latter poses a problem, especially for critically ill patients, making it desirable to employ real time acquisition. To maintain uncompromised spatial and temporal resolution acceleration factors of $R \approx 8$ -10 are required. Using parallel imaging methods alone, these accelerations lead to a substantial noise enhancement. Therefore, the purpose of this study was to combine parallel imaging with compressed sensing ([6], [7], [8]) in order to perform high quality functional cardiac imaging.

<u>Materials and methods:</u>
In the presented reconstruction the two accelerating techniques are performed subsequently (Fig. 1)). Both parts relied on spin warp imaging accelerated in phase encoding direction. Beginning with the compressed sensing, a k-space with equidistant undersampled lines is reconstructed from a strongly incoherent undersampled k-space. The GRAPPA algorithm fills in the missing lines, which finally leads to a completely reconstructed Nyquist sampled k-space. Combining an acceleration factor of 2.1 for compressed sensing and an acceleration factor of 4 for parallel imaging leads to an adequate acceleration factor (i.e. >8) for the real time acquisitions.
The precondition of compressed sensing, i.e. having a sparse representation of the object, is fulfilled by creating difference images between each temporal phase of the beating heart and a temporal averaged image. The incoherent undersampling is changed from phase to phase to fill a complete k-space with less temporal resolution, like in UNFOLD [4] or Auto-SENSE [5]. Compressed sensing was realized by an algorithm after Ma et al. [2] which solves the Lagrangian version of the compressed sensing problem:

$$\underset{x}{Min}\left(\|x\|_1 + \|Ax-y\|_2^2 \right),$$

where **x** is the image to be reconstructed, **y** the undersampled k-space and **A** a partial Fourier matrix. Performing compressed sensing leads to an equidistant undersampled k-space for every receiver channel. In the second part of the reconstruction a standard GRAPPA reconstruction [3] (calibrated in a pre scan) is performed.
For a simulation to test the algorithm, data from a routine cine examination (TrueFisp, 3T Trio, Siemens Healthcare, Erlangen, TR 3.1ms, TE 1.37ms, temporal resolution 46.5ms, 32 channel body array coil) were reduced from 168 phase encoding steps to 20.
Finally, a real time sequence using the required undersampling scheme, was implemented and tested with a SSFP sequence (TrueFisp, 3T Trio, Siemens Healthcare, Erlangen, TR 3.0ms, TE 1.49ms, temporal resolution 59.4ms, 32 channel body array coil). In this case, g-factor maps were calculated similar to Robson et al. [1] to rate the image quality.

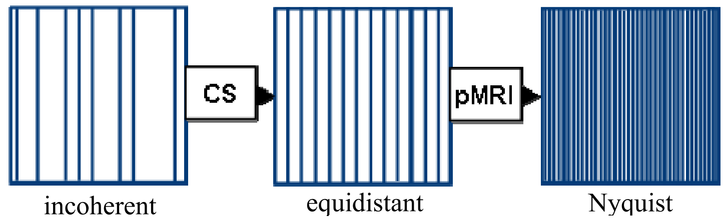

***Fig. 1)** k-spaces with undersampling in phase encoding direction, the incoherent k-space is the measured one*

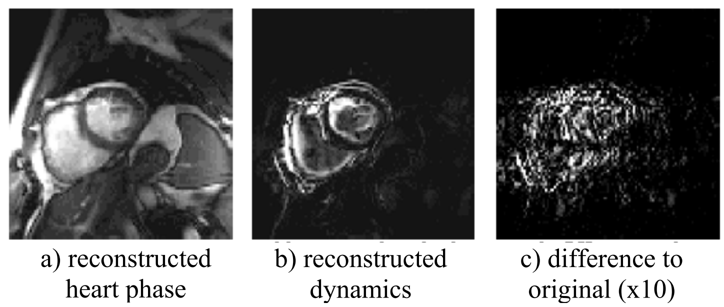

***Fig. 2)** example for one heart phase of the simulated reconstruction and its dynamics*

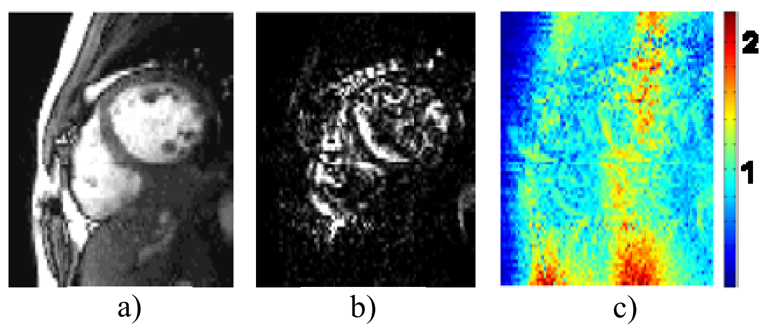

***Fig. 3)** a) one heart phase of the real time measurement; b) reconstructed dynamics of a); c) g-map for the reconstructed dynamics*

<u>Results:</u>
Fig. 2) shows a representative reconstructed time frame for the simulation (**a**) and its reconstructed dynamics (**b**), i.e. the difference image between time frame and average. Fig 2c) displays the difference between the image reconstructed from the full k-space and the compressed sensing reconstruction of the undersampled data. The amplitude is multiplied by a factor of 10 in comparison to Fig. 2 a) and b) to emphasise the differences.
Fig. 3) shows the results for the real time measurement, again for a representative heart phase. The reconstruction results in high resolution images without visible artefacts, both for the real time acquisition and the simulated reconstruction. For a temporal resolution of 20 frames/s the images show an excellent SNR. The determined g-factor map with values < 2 in the heart region underlines the great signal-to-noise properties of the CS-GRAPPA reconstruction even for acceleration factors > 8.

<u>Conclusion</u>
The described CS-GRAPPA combination allows imaging with very high acceleration factors. Real-time examinations of the heart dynamics with high temporal and spatial resolution can be performed without significant loss of image quality. The very small errors for the simulated data set, as well as the low g-factors prove the excellent image quality of the proposed real time acquisition.

<u>References:</u>
[1] Robson, MRM, 60: 895-907 (2008); [2] Ma, CVPR, 1-8 (2008); [3] Griswold, MRM 47:1202-1210 (2002); [4] Madore, MRM, 48, 493-501 (2002), [5] Köstler, JMRI, 18: 702-708 (2003); [6] Donoho, IEEE Trans. Inform.Theory 52: 1289-1306 (2006) [7] Candès, IEEE Trans. Inform. Theory 52: 489-509 (2006) [8] Lustig, MRM 58: 1182-1195 (2007)