# Taming an Ill-Conditioned SPIRiT: Improved Iterative Image Reconstruction for Real-Time Cardiac MRI

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**Purpose:** The iterative self-consistent parallel image reconstruction technique (SPIRiT)[1] exhibits distinct advantages over GRAPPA; additional self-consistency constraints between acquired and unacquired data allow for improved image reconstruction in terms of SNR. Yet the use of SPIRiT in the specific context of free-breathing real-time cardiac imaging can be challenging. The use of high acceleration rates needed to meet temporal resolution requirements in the presence of severe breathing motion can lead to ill-conditioning of the SPIRiT reconstruction, introducing local minima corresponding to results with elevated artifacts due to loss of solution uniqueness. In many scenarios, elevated artifact levels can have a more significant impact on image diagnostic quality than does reduced SNR. The introduction of incoherence via random k-space sampling schemes can help address ill-conditioning; however, free-breathing real-time cardiac cine precludes the use of 3D data acquisition necessary for spatially incoherent sampling. Dynamic 2D cine imaging offers the possibility of incoherent k-t sampling schemes with the additional use of temporal regularization; however, such approaches can be computationally intensive and may still not adequately address the ill-conditioning of SPIRiT. Here, we demonstrate that the use of a GRAPPA starting point can help address this issue of ill-conditioning in SPIRiT when incoherent k-space sampling is challenging, and thereby improve both image diagnostic quality by reducing artifact level and also reconstruction time by improving convergence.

**Methods:** Free-breathing cine data (rate 6, 256 frames, 32 channels) were acquired at 1.5T (Siemens, Avanto) in two healthy volunteers in three slice orientations (horizontal 2- and 4- chamber and short axis). A temporally interleaved, uniformly downsampled, Cartesian trajectory was used. Data were reconstructed using SPIRiT with a 7x7 kernel. For simplicity, the POCS method was used. Two different starting points were evaluated: (1) zero-filled (ZF) in which unacquired data points were initialized to zero, and (2) GRAPPA initialization using a 4x5 kernel. SPIRiT and GRAPPA kernel estimation were performed using the temporal average of all frames as the full k-space input. An RMS difference between iterations of 4e-3 was used as a stopping point. Artifact levels were quantified using a correlation technique, and the average SNR over all 256 frames was estimated based on random matrix theory[2]. To achieve fast reconstruction times, all techniques were implemented in C++ using the GPU libraries provided within the Gadgetron framework[3]. Reconstructions were performed on an Intel Core i7 workstation with a single GPU card (NVIDIA GTX580) and 24Gb memory.

**Results:** Figure 1 demonstrates that the use of a GRAPPA initialization improves image quality by significantly reducing artifact levels, although with a slight reduction in SNR compared to a ZF initialization. Figure 2 shows the artifact levels averaged across all 256 frames for both volunteers and all slice orientations. All artifact levels were significantly reduced ($p < 0.0001$) in results using GRAPPA initialization compared to those using ZF initialization. The average number of iterations until convergence was reduced from 57 iterations for ZF initialization to 9 iterations for GRAPPA initialization. Within the Gadgetron framework, average reconstruction time per iteration per frame for both techniques was 6ms. Thus, for a typical 40 frame cine series, the reconstruction time was only 2.2s for GRAPPA initialized SPIRiT compared to 13.7s when ZF initialization was used.

**Conclusion:** The use of a GRAPPA initialization to address the ill-conditioned nature of SPIRiT can increase the clinical relevance of this technique by reducing the introduction of artifacts due to local minima and dramatically reducing reconstruction time. With the use of fast $\ell_1$-regularization techniques, we expect that SNR may be gained while not sacrificing the artifact reduction demonstrated in this work.

**References: 1.** Lustig M, Pauly JM. SPIRiT: Iterative self-consistent parallel imaging reconstruction from arbitrary k-space. Mag. Res. Med. 2010; 64(2): 457-71. **2.** Ding Y, Chung YC, Jekic M, Simonetti OP. A new approach to autocalibrated dynamic parallel imaging based on the Karhunen-Loeve transform: KL-TSENSE and KL-TGRAPPA. Mag. Res. Med. 2011; 65(1): 1786-92. **3.** Hansen MS, Sørensen TS. Gadgetron: An open source framework for medical image reconstruction. Mag. Res. Med. 2012; doi:10.1002/mrm.24389.

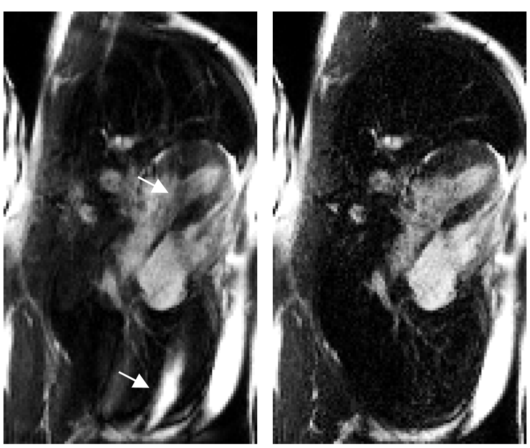

**Figure 1:** Example SPIRiT image reconstruction results using a zero-filled initialization (**left**) and a GRAPPA initialization (**right**). Artifacts (**white arrows**) are reduced when a GRAPPA initialization is used.

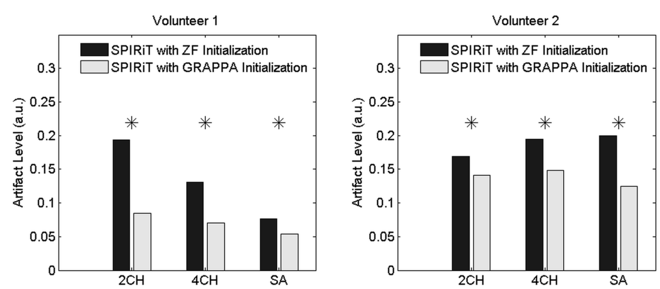


**Figure 2:** *In vivo* (rate 6) comparison of mean artifact levels for both volunteers averaged over all 256 frames for ZF and GRAPPA initialization. Stars indicate statistically significant ($p < 0.0001$) reduction in artifact level between the two methods.