# Compressed Sensing Reconstruction with an Additional Respiratory-Phase Dimension for Free-Breathing Imaging

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**Introduction:** Respiratory motion degrades image quality and reduces the performance of compressed sensing (CS) [1] since temporal sparsity is decreased. To minimize the effects of respiratory motion, MRI data acquisition can be performed during breath-holds, or using navigator or respiratory-bellow gating. However, breath-holds are subject dependent with limited duration in patients and the use of navigator or respiratory-bellow gating requires long acquisition times to acquire data during an interval of moderate respiratory motion. Non-Cartesian imaging offers the possibility of self-gating by estimating the respiratory-motion signal from the oversampled k-space center. However, most current gating techniques are inefficient since they only use the data acquired during an interval of moderate respiratory motion (eg. expiration) and discard the rest, which correspond to a large percentage of the total amount of acquired data. Although the discarded data corresponds to different respiratory phases, it is highly correlated and can therefore be used for reconstruction using a CS approach. We have recently introduced Golden-angle RAdial Sparse Parallel MRI (GRASP) [2] that combines CS and parallel imaging for golden-angle (GA) radial sampling to enable highly accelerated dynamic MRI. In this work, we incorporate a respiratory motion compensation framework into GRASP for highly-accelerated free-breathing MRI by (a) reconstructing one respiratory phase (e.g. expiration) with self-gating (SG-GRASP) and (b) reconstructing data with an additional respiratory-phase dimension created by sorting the acquired data into multiple respiratory phases with self-gating (SG-MP-GRASP).

**Methods:** ***Data Acquisition, Self-Gating and Retrospective Data Sorting:*** Fig. 1 shows the acquisition for GA radial sampling employed in GRASP [2]. In order to perform self-gating in 3D imaging, all slices for a given projection angle need to be acquired sequentially before proceeding to the next angle. The k-space center ($k_x$=$k_y$=0 for 2D and $k_x$=$k_y$=$k_z$=0 for 3D) in each projection angle (light green dots in Fig 1a&b) was used to obtain the temporal variation caused by physiological motion such as respiratory or cardiac motion. Clean motion signals can be obtained with a band-pass filter (Fig 1c&d). In cardiac imaging, where signal variation includes both respiratory and cardiac motion occurring simultaneously but with different temporal frequencies, the motion signals can be separated by performing a band-pass filter centered at each frequency [3]. For multicoil acquisitions, coil elements that are close to the heart and liver-lung interface can be used for respiratory and cardiac gating respectively, as shown in Fig1c&d. Given the detected respiratory motion signal, the data corresponding to the expiratory phase were first gated for reconstruction (SG-GRASP data). In a second more general approach, all the acquired data were sorted into different respiratory phases, to form the additional respiratory-phase dimension (SG-MP-GRASP data). Note that both sorted data sets are undersampled. The rectangular dark green boxes in Fig 1d indicate gated respiratory phases with equal numbers of spokes in each phase.

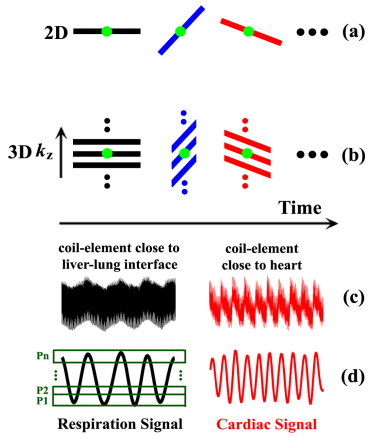


**Fig1.** (a) 2D and (b) 3D GRASP acquisitions. Motion signals can be obtained from the center of k-space (light green dots) followed by a filter (c&d). Different respiratory and/or cardiac phases can be generated according to the detected respiratory/cardiac signal.

***Imaging Reconstruction:*** Following data sorting, SG-GRASP reconstruction was performed following the GRASP algorithm described in [2]. For SG-MP-GRASP, where data has increased dimensionality, the reconstruction was extended to minimize the following objective function: $\|E\bullet x-y\|_2+\lambda_1\|T_1\bullet x\|_1+\lambda_2\|T_2\bullet x\|_1+\cdots+\lambda_n\|T_n\bullet x\|_1$, where x is the image to be reconstructed, y is the sampled measurements in radial k-space and E is the Fourier transform operator incorporating NUFFT operation [4]. $T_n$ is the sparsifying transform performed along the $n^{th}$ dynamic dimension and $\lambda_n$ is the weighting parameter. For static imaging, n=1 which is the additionally constructed respiratory dimension and for dynamic imaging, n>=2 including the original dynamic dimensions (eg. cardiac contraction) and the respiratory dimension. In the reconstruction, only temporal sparsifying transforms were used and the λ's were empirically determined by comparing the performance of several values.

***Imaging Studies:*** Cardiac cine imaging was performed on a healthy volunteer (male, age=26) during free breathing without external cardiac or respiratory gating in a 3T MRI scanner (TimTrio, Siemens) with a 12-element receive coil. A 2D SSFP pulse sequence with GA radial sampling was employed to acquire one mid short axis slice with matrix size=192x192. 4800 continuous spokes were acquired in 15s including a 1s dummy scan for steady state. FOV=320x320mm, slice thickness =10mm, TR/TE=3.1/1.34ms and FA=50°. SG-GRASP reconstruction was performed using data acquired during expiration with matrix size=192x192x30, where 30 phases were reconstructed for one cardiac cycle. The whole data set was also sorted into 6 respiratory phases for SG-MP-GRASP reconstruction with matrix size=192x192x30x6. 24 spokes were used for each phase, which corresponded to an acceleration rate of 12.6. Liver imaging was performed on another volunteer (male, age=29) during free breathing without external gating in the same MRI scanner. A 3D TurboFLASH pulse sequence with stack of stars GA radial sampling was implemented and 14 slices were acquired in coronal view with in-plane matrix size=224x224. 1000 continuous spokes were acquired for each slice with FOV=300x300 mm, slice thickness=10 mm, TR/TE=3.47/1.52ms and FA=12°. SG-GRASP (static images) reconstruction was performed using data acquired during expiration with matrix size=224x224x14 and SG-MP-GRASP (dynamic images) reconstruction was performed by sorting the whole data set into 6 respiratory phases with matrix size=224x224x14x25. 40 spokes were used for each phase, which corresponded to an acceleration rate of 8.8. Reconstruction was implemented in MATLAB (MathWorks, MA) using a non-linear conjugate gradient algorithm and total variation (TV) as the sparsifying transform for each temporal dimension. For SG-GRASP reconstruction in liver data, 2D spatial TV was used as the sparsifying transform due to the lack of temporal dimension. The weighting parameters were chosen empirically after comparing the performance of different values.

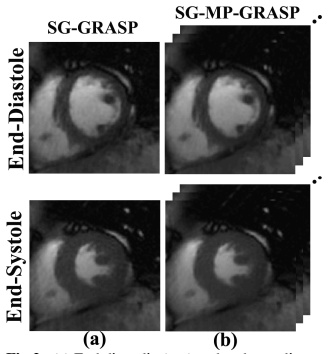


**Fig 2.** (a) End diastolic (top) and end systolic (bottom) images reconstructed with data self-gated in expiration. (b) End diastolic (top) and end systolic (bottom) images reconstructed from multiple respiratory phases, which constitute an additional dynamic dimension.

**Results:** Fig 2 shows representative cardiac cine images of end-diastole and end-systole from SG-GRASP (1 respiratory phase) and SG-MP-GRASP (6 respiratory phases). Both reconstructions presented adequate image quality with SG-MP-GRASP having improved performance as demonstrated by the lower level of residual aliasing artifact when cine movies are played (not shown). Fig 3a shows liver image from a representative partition without self-gating. Fig 3b shows liver image from SG-GRASP (1 respiratory phase) and Fig 3c shows image from SG-MP-GRASP (25 respiratory phases). Sharper liver vessels can be observed in Fig 3c.

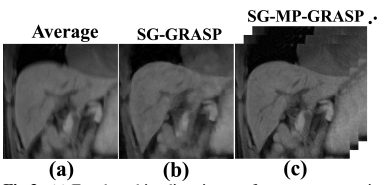


**Fig 3.** (a) Free breathing liver images from a representative partition without self-gating. (b) Self-gated liver images with one respiratory phase. (c) Self-gated liver images with multiple respiratory phases constituting an additional dynamic dimension.

**Discussion:** Sorting the acquired golden-angle radial data to create an additional respiratory-phase dimension increased the overall multidimensional sparsity and incoherence for compressed sensing reconstruction at the only expense of higher computational burden. The proposed technique can be useful to reduce the acquisition time of current navigator-supported free-breathing approaches by exploiting correlations in the whole data set instead of discarding data in different respiratory phases. Moreover, it also offers possibility of exploiting temporal correlation and sparsity for CS reconstruction in static imaging.

**Reference:** [1] Lustig M, et al. MRM 2007; 58:1182-1195. [2] Feng L, et al. ISMRM 2012 p 81. [3] Liu J, et al. MRM 2010; 63:1230–1237. [4] Fessler. IEEE T-SP 2003 51(2):560-74.