# Improving Scan Efficiency of Respiratory Gated Imaging Using Compressed Sensing with 3D Cartesian Golden Angle Sampling

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**Introduction:** Navigator gating methods are used to reduce the effects of motion during free breathing MRI. To cope with potential changes of the breathing pattern over time, a multi-gating window method (PAWS) [1] was proposed. It uses multiple gating bins rather than one predefined gating window. The final image in PAWS is reconstructed from the bin that is completely filled first. All other data are discarded. Recently, it was proposed to use also the incomplete data from the bins usually rejected to reconstruct images at different respiratory phases [2,3]. However, these methods are based on 3D radial trajectories, which require an increased amount data to be acquired, prolonged reconstruction time (especially evident in iterative reconstruction methods), and more importantly a loss of SNR (up to 20%) [4], compared to Cartesian sampling.

In this work, we propose a Cartesian k-space sampling strategy for PAWS data acquisition and applying compressed sensing (CS) [5,6,7] for the reconstruction of images from incompletely sampled bins. Image registration is used to combine data from all bins in the final reconstruction step.

**Methods:** *Data acquisition:* Data in 3D Cartesian k-space are acquired in TFE trains along radial spokes in the phase encoding ky-kz plane. The ky-kz coordinates in each spoke lie on a Cartesian grid in an approximate radial fashion (Fig.1). The temporal acquisition order of the radial spokes is determined according to the golden ratio $\varphi = 0.618$ [8]. To ensure a complete coverage of k-space in minimal number of radial spokes, the ky-kz plane is segmented and spokes ordering is perfomed as a permutation of the predefined segments. The trajectory enables an irregular quasi-isotropic distribution of the measured data in multiple respiratory phases at all times, which is favorable for CS (Fig.2). Data acquisition is terminated after any of the bins has obtained k-space coverage greater than a predefined threshold.



**Fig.1 Sampling trajectory.** *Data in 3D Cartesian k-space are acquired in multiple TFE trains along radial spokes in ky-kz. The spokes are ordered temporally according to the golden ratio.*

*Reconstruction:* A combined CS-SENSE reconstruction was applied to reconstruct images from the undersampled data in each bin. The reconstruction was performed by minimizing the function:

$$f(x) = \sum_i \left\| S_i F_u x - y_i \right\|_2^2 + \left\| \Psi x \right\|_1 , \qquad (1)$$

where $F_u$ is the undersampled Fourier transform, $y_i$ and $S_i$ are the k-space data and the coil sensitivity for a coil i and $\Psi$ is the sparsifying transform. 3D affine image registration [9] was performed and the motion corrected data are combined to obtain the final image.

*Measurements:* In vivo experiments on three healthy volunteers were performed on a 1.5T clinical scanner (Achieva, Philips Healthcare) using a 5 channel cardiac coil. An ECG triggered, navigator-gated, magnetization prepared (T2-prep, fat suppressed), 3D balanced FFE sequence (5bins, 5mm width) was performed with the following parameters: TR/TE = 3.7/1.86 ms, TFE factor 32, FOV = 300x256x160 mm$^3$, 192x164x40 matrix, flip angle 60°. Images for



**Fig.2 PAWS gating scheme.** *a) the respiration navigator, measuring the diaphragm displacement over time, is used to distribute the measured signal into bins. Using a golden ratio Cartesian trajectory variable density irregular sampling is obtained in all bins b).*

each bin were reconstructed according to Eq. 1, using D4 wavelets as sparsifying transform. Reconstruction time for each 3D data set was 2 min.

**Results:** Results of the CS-SENSE reconstruction for each bin are shown in Fig 3 for a selected slice of the 3D data. The fraction of the k-space measured in each bin is indicated above the images. The final combined image shows improved image quality compared to the images from the individual bins. The combined image shows well defined RCA origin and more homogeneous representation of the blood pool.

**Conclusion:** A method for improving the efficiency of respiratory gated acquisition was presented based on 3D Cartesian acquisition in combination with compressed sensing. The method could be used to either reduce the scan time or improve the SNR. Very good image quality and SNR was obtained by independently reconstructing separate images for each bin and using all data only in the final combination step. Further improvement of the method includes a second CS reconstruction step using the data from all bins in which the estimated motion field is used as an additional constraint in the reconstruction.
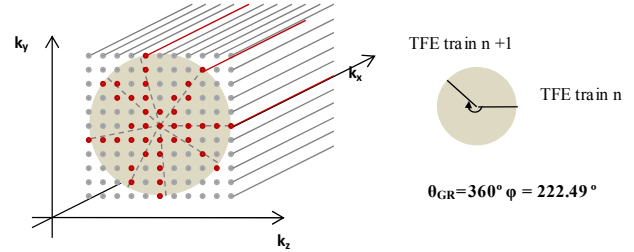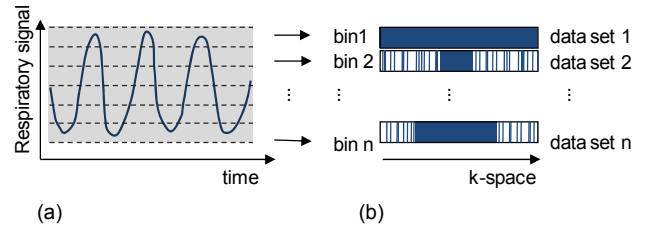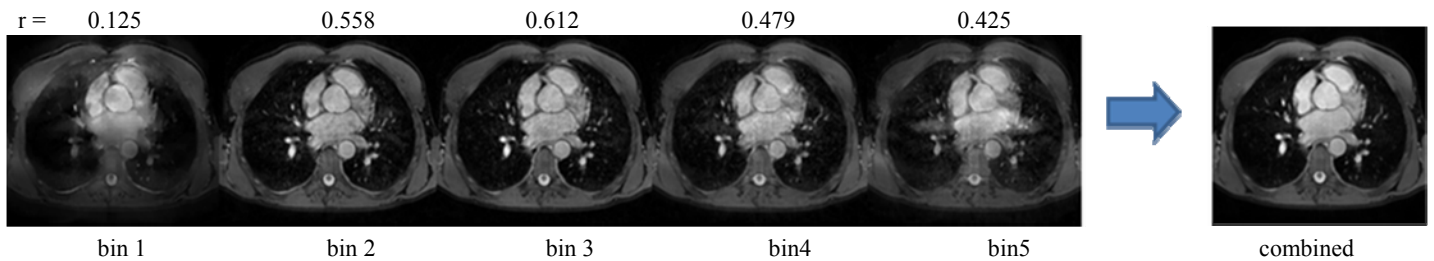


**Fig. 3 CS PAWS reconstruction.** *Images, reconstructed from incomplete data using CS, are shown for each bin. The corresponding fraction of the measured k-space is given above. The combined image registered to the motion state of bin 3 is shown on the right.*

**References:** [1] Jhooti P. et al., MRM 2000 43:470-480; [2] Baht H. et al., ISMRM 2010 #669;  [3] Buerger C. et al., ISMRM 2010 #3057 [4]  Pipe J et al., MRM 1995, 34: 170-8 [5] Candes E et al, IEEE Tran Info Theo 2006 52: 489-509; [6] Donoho D, IEEE Tran Info Theo 2006 52:  1289-1306;[7] Lustig M et al, MRM 2007, 1182-1195; [8]Winkelmann et al, Trans Med Imag 26:68-76 [9] Thevenaz P. et al. IEEE Tran Image Proc 1998 7:27-41.