Floating slice whole-body MRI using a continuous moving bed, golden angle radial acquisition, and compressed sensing reconstruction

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TARGET AUDIENCE: Clinicians and researchers interested in rapid, flexible whole-body imaging, continuous moving bed imaging, and compressed sensing.

PURPOSE: To enable rapid, whole-body gradient echo imaging with post-scan flexible slice partitioning and high image quality.

METHODS: Using a continuous moving bed coupled to a Philips Achieva 3.0 T scanner (Philips Healthcare, Best, The Netherlands), free-breathing data was acquired on healthy volunteer. The table speed was 20 mm s^{-1}, and the imaging protocol employed a continuous 2D golden angle radial gradient echo sequence with TR/TE = 7.64/3.45 ms, axial FOV = 53 cm, flip angle = 20°, nominal excited slice thickness of 8 mm, and readout matrix size of 264. A total of 9,815 radial profiles were collected using the quadrature body coil, for a total imaging time of 75 s, an effective superior-to-inferior (SI) FOV of 150 cm, and a linear profile density of 65.4 cm^{-1} in the SI direction. The axial in-plane voxel size was 2 mm x 2 mm.

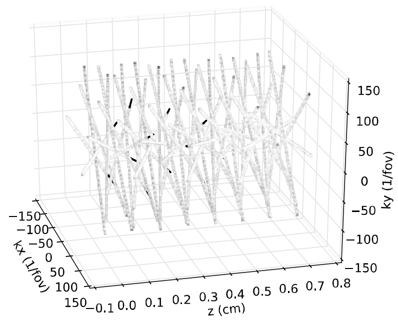


Figure 1: The first 50 radial profiles in this experiment. Note the uniform k-space coverage, which allows flexible shifting of the reconstructed slice location or thickness after data acquisition.

In a continuous golden angle radial acquisition, a single radial readout is rotated in 111.25° increments around the center of k-space. Figure 1 shows the first 50 radial profiles in such an acquisition. Golden angle sampling in this experiment produces a uniformly covered k-space no matter how the data are grouped in the SI direction. Thus "slices" become untethered from the slice excitation locations and can be defined as any grouping of the profiles, with arbitrary centers and thicknesses within the scan volume. Slices can also overlap or be gapped. If thinner slices are reconstructed, more artifacts will be seen, but less through-plane signal averaging will occur, and vice versa. Compressed sensing reconstruction minimizes undersampling artifacts from taking thinner slices and consequently fewer profiles, thus reducing volume averaging or increasing SNR for similar image quality.

The complex data were reconstructed slice-by-slice both with a standard gridding reconstruction and iteratively by solving the following optimization problem:

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} \alpha \mathrm{TV}(\boldsymbol{x}) + \beta\|\boldsymbol{x}\|_1 + \tfrac{1}{2}\|\boldsymbol{A}\boldsymbol{x} - \boldsymbol{b}\|_2^2, \quad (1)$$

where TV is the total variation, $\boldsymbol{A}$ is the undersampled non-uniform Fourier transform, and $\boldsymbol{b}$ is the collected data, and α and β are weighting factors, hand-tuned in this problem to be 0.01 and 0.05, respectively. To solve Eq. (1), we used the FCSA algorithm[1] because it is fast and allows joint penalties. The TV was computed in the axial plane only and the reconstruction was applied slice-wise for the chosen slice positions and thicknesses.

RESULTS: Fig. 2 shows coronal slices through the mid-plane with a standard gridding (left) and the compressed sensing reconstruction (right) using a 20 mm slice thickness. Fig. 3 shows the effect of altering the slice thickness. Panel (b) is a 20 mm slice, and (c) and (d) are two 10 mm slices made from splitting the data from the 20 mm slice in (b). Features that are averaged together in the thick slice become distinguishable on the 10 mm slices, while the level of artifact increases. Panel (a) shows the original gridding reconstruction of the 2cm slice, to highlight the improvement that the CS reconstruction provides.

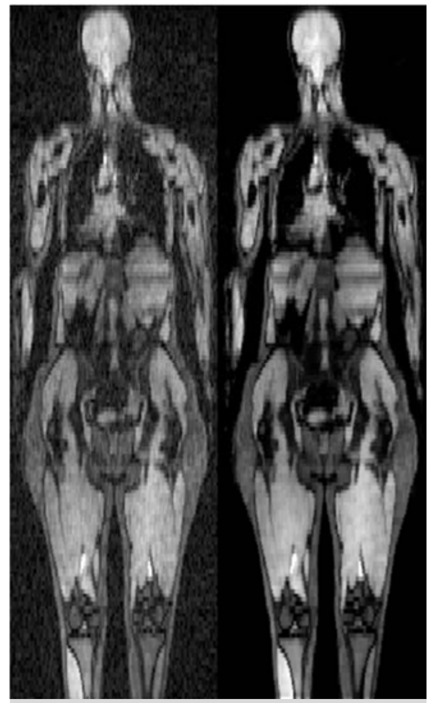
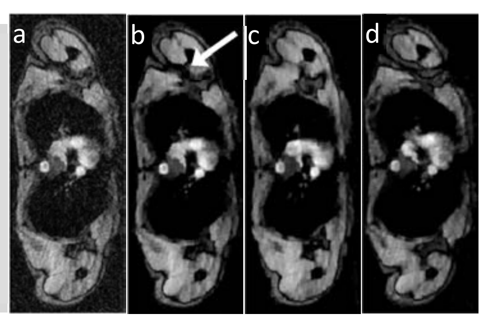


Figure 2: Free breathing, whole body volume (150 cm SI FOV) acquired in 75 s at 2 mm x 2 mm in-plane with phase encode density of 65.4 cm^{-1} in the SI direction. The equivalent undersampling factor is 7.0. The sparsity-constrained reconstruction in Eq. 1 (right) greatly reduces the artifacts from undersampling (left).

DISCUSSION: In Fig. 2, banding in the liver is noticeable due to free breathing, but other than that motion artifacts are relatively benign. Some smoothness could be gained in the slice direction if the TV were extended to penalize the gradient in that direction as well. One of the primary limitations of the image quality (for a given scan time) in this protocol is the scan TR. The lower the TR, the higher the profile density in the SI direction, and the more data can be used to reconstruct a slice of a given position and thickness. Decreasing the table speed can also yield higher quality images, but with a consequent increase of scan time. Acquiring with a multichannel coil and using a CLEAR reconstruction[2] could also improve SNR and reduce artifacts beyond our results here.

CONCLUSION: Continuous moving bed MRI[3,4] has shown promise for enabling efficient whole-body imaging. We have developed a rapid, T_1-weighted, whole body, free-breathing protocol using a continuous moving bed and golden angle radial imaging coupled with a compressed sensing reconstruction that can produce a high SNR, whole-body image volume in 75 s with the freedom to select arbitrary slice positions and thicknesses for later analysis.

Figure 3: Zoomed axial slices through the chest showing volume averaging in a 2 cm reconstructed slice (b) that is reduced the data is split into two 1 cm slices (c, d) and reconstructed with CS. Image (a) shows the original 2-cm slice gridding reconstruction.



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