Real-time cardiac MRI using manifold sensing

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Target Audience – This work caters to researchers interested in the recovery of real time dynamic MR images from highly under-sampled k-space data. The algorithmic tools are quite general and can be applied when the images in the time series lie on a low dimensional manifold; for example, free breathing cardiac, lung & abdominal imaging and imaging of vocal cavity during speech.

Purpose – The main focus of this work is to enable free-breathing and un-gated cardiac MR images from highly under-sampled k-space data. This scheme eliminates the need for multiple breath-holds to evaluate cardiac function, thus increasing patient comfort. Since the proposed approach does not require cardiac and respiratory gating or manual self-gating, it can be automated for routine clinical use. This scheme can work for a range of existing k-space trajectories, including golden angle radial sequences.

Methods – Each image in the free breathing cardiac MRI series can be expressed as a non-linear function of 2 parameters: cardiac phase and respiratory phase. Hence, the images can be assumed to lie on a smooth 2-D manifold in a space whose dimension is equal to the number of pixels in each image. This is illustrated on the PINCAT phantom[1] in Fig 1. Note that images with similar cardiac and respiratory phases are closer on the manifold, while images differing in the phases are well separated. We express the recovery of the image series as a weighted l1 minimization:

$$X = \arg\min \sum_i ||A_i X - b_i||_2^{\,2} + \gamma \sum_j \sum_k ||W_{jk}(X_j - X_k)||_1 \quad (1)$$

Here X is the recovered image series, A_i is the forward operator for the i^{th} coil, b_i is the raw k-space data acquired by the i^{th} coil, γ is the regularization parameter and W_{jk} are scalars indicating degree of similarity between the j^{th} and k^{th} images (high if the images are close on the manifold, low if they are far away). Since we only have under-sampled data, the main challenge is the computation of the exact distance between points to determine the weights. Recent work in manifold embedding[2] shows that inter-image distances can be accurately estimated from a few under-sampled measurements of each image acquired at identical k-space locations. The outline of the reconstruction scheme is shown in Fig 2. Inter-image distances and hence weights are computed from k-space measurements at the same locations for each image. Once the weights are determined, the image series is reconstructed by solving (1) using all the acquired k-space samples. The incoherence of measurements between frames is required to make (1) well posed and hence provide good quality reconstructions.

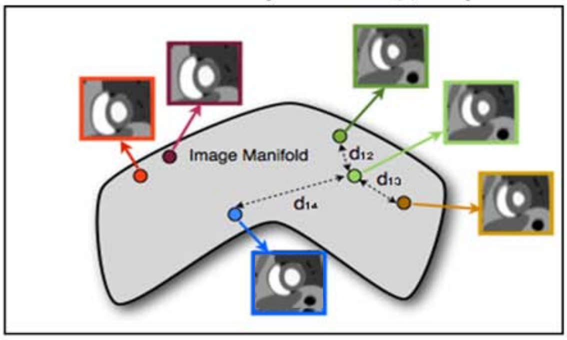

Fig 1: Illustration of the manifold structure of images. Cardiac free breathing images can be considered to live on a smooth 2D manifold in higher dimensional space. We exploit the smoothness of the data on the manifold to recover highly under-sampled data. Specifically, the regularization term in (1) penalizes the l1 norm of the difference between images that are closer on the manifold more heavily than between images that are well separated on the manifold.

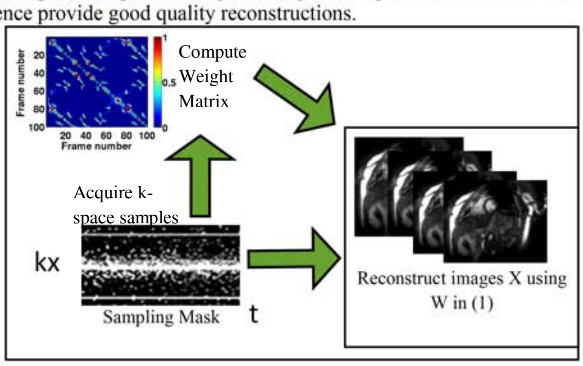

Fig 2: Image reconstruction pipeline of the proposed scheme. We propose to use a sampling pattern which consists of two parts. Specifically, a subset of the samples is used to acquire each image at the same k-space location. The rest are incoherently distributed. We use the k-space data from the same locations to estimate the weights. The weights and all acquired k-space samples are used to solve (1), thus exploiting the manifold structure of the dataset.

We performed cardiac cine imaging on a healthy male volunteer (age 24 yrs) in the free breathing mode without any external gating on a 3T MR scanner (Siemens, Trio) with a 12-element receive coil. A SSFP pulse sequence with golden angle radial sampling was used to acquire a single short-axis slice with matrix size 128x128, FOV = 300mm x300mm, slice thickness = 5 mm, TR/TE = 3.94/2 ms and FA = 64°. For the purpose of reconstruction we used 9000 lines of k-space. In this work, we estimate the weights from central k-space data which is acquired during each frame. The sequence will be modified in the future to accommodate more similar samples in the future, which is expected to further improve performance.

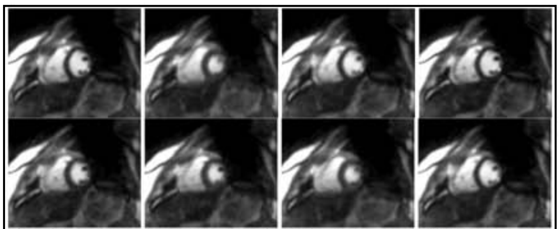

Fig 3: A few reconstructed images from the dynamic image dataset obtained by solving (1). Weight between images in similar cardiac and respiratory phase is kept high. The weights are determined using the profiles of the central k-space data.

Results – We used 15 lines per frame to reconstruct 600 frames of the entire dataset. A subset of the frames is shown in Fig 3. The reconstructed images are cropped to show only the myocardium (which is the main region of interest).

Discussion – While these results are preliminary, the images are observed to exhibit low spatio-temporal blurring and aliasing. This demonstrates the potential of the method in automatically detecting redundancies in the image time series and exploiting them to considerably reduce the sampling requirements.

Conclusion – The proposed method can be used to acquire free-breathing cardiac cine images. This would eliminate the need for time consuming multiple breath-holds. It would also help patients who are unable to hold their breath for a long time. We expect the proposed scheme to generate considerable impact in lung, cardiac, abdominal, and speech imaging.

References – 1. B.Sharif,Y.Bresler. Physiologically improved ncat phantom (pincat) enables in-silico study of the effects of beat-to-beat variability on cardiac MR. ISMRM 2007
2. Michael B. Wakin. Manifold-based signal recovery and parameter estimation from compressive measurements. arXiv:1002-260