Manifold Learning based ECG-free free breathing cardiac MRI for highly accelerated CINE

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Introduction: ECG gated breath-hold acquisition is normally used for the functional assessment of the heart. However, the external ECG signal is not always reliable at higher magnetic field strengths and is difficult to obtain in patients with arrhythmia[1]. Free breathing gated acquisitions can be performed when patients present difficulty in holding their breath. This is usually achieved by using navigator echoes or bellows to track the displacement of the diaphragm. However, these techniques need long setup times and careful calibration. Hence, it is highly desirable to get both cardiac ECG and respiratory signals directly from the acquired data. Recently, manifold learning (ML) approaches[2] have been used in MRI to extract meaningful dimensions (manifolds) from the high-dimensional set of images. An example is respiratory self-gating where low dimensional (1D) respiratory signal with high correlation to the external navigator has been extracted from a set of fully sampled free breathing images[3]. In this work, we propose to use ML technique to estimate both the cardiac and respiratory signals from a sequence of real time images reconstructed from highly undersampled data and use it to achieve respiratory motion free CINE imaging. Prospective free-breathing golden radial cardiac MR acquisitions, performed in 5 volunteers, demonstrate the feasibility of ML approach for both cardiac and respiratory gating.

Theory: ML techniques, such as Laplacian Eigenmaps (LE)[2-3], extract the underlying low dimensional signal while preserving the structure of the higher-dimensional data set. LE preserve the structure of the data set by ensuring data points which are close in the high dimensional space remain close in the low dimensional embedding. This is achieved by minimizing a weighted Euclidian distance based cost function. Considering a sequence of images $\mathbf{x_1}, \mathbf{x_2},..,\mathbf{x_T}$ where each image resides in a high N-dimensional space (N being number of voxels per image), the cost function to be minimized is given by $\arg\min \sum_{ij} \|\mathbf{s}_i - \mathbf{s}_j\|_2^2 W(\mathbf{x}_i, \mathbf{x}_j)$ where $\mathbf{s_1}, \mathbf{s_2},..,\mathbf{s_T}$ are the corresponding points in a low K-dimensional space and $W(x_i,x_i) = \exp(-\|\mathbf{x}_i - \mathbf{x}_j\|_2^2/2\sigma)$, with σ weighting the influence of neighbouring pixels.

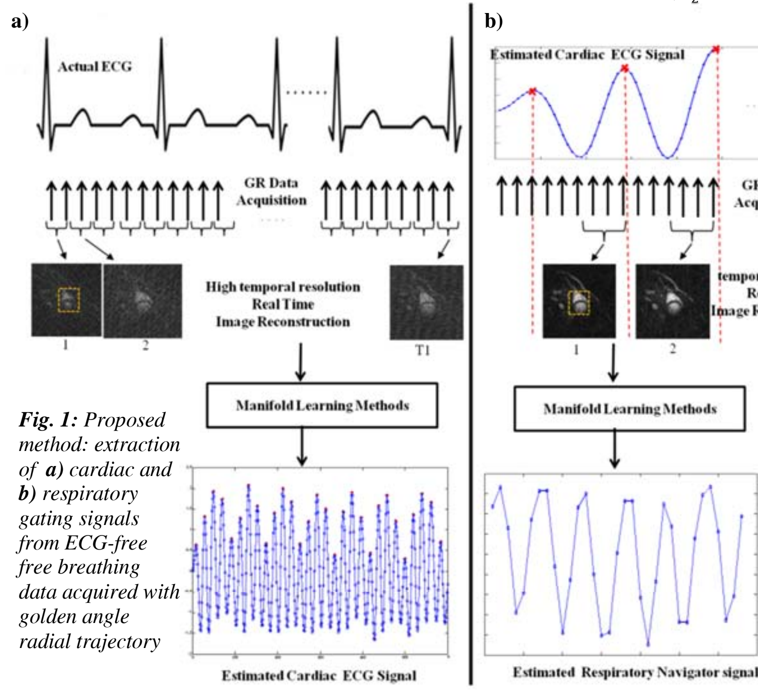

*Fig. 1: Proposed method: extraction of **a)** cardiac and **b)** respiratory gating signals from ECG-free free breathing data acquired with golden angle radial trajectory*

Method: The k-space data are acquired continuously without ECG gating and under free breathing using golden angle radial trajectory[4]. This trajectory allows retrospective adjustment of any arbitrary temporal resolution and exhibit incoherent artefacts. For one of the coils having high sensitivity over the heart, high temporal resolution (HTR, 40-60 ms) real time images are reconstructed via gridding. The ML technique is applied to the HTR images in a region of interest (ROI) around the heart to estimate the 1D cardiac signal (Fig.1a). A peak detection algorithm is used to derive the R-wave peaks (red dots in Fig1a) in the cardiac signal to mark the start of each cardiac cycle. Using the estimated cardiac ECG signal, low temporal resolution (LTR, 100-200ms) images are reconstructed in mid-diastole for each cardiac cycle. ML technique is applied to the LTR in the ROI to estimate the 1D respiratory signal (Fig.1b). An acceptance window (1/3 of the whole respiratory signal extent) near the end expiration is defined for respiratory gating. To achieve accelerated MR imaging, the data in the gating window is undersampled and final gated reconstruction is done using kt-Sparse SENSE[5] method with x-y-f space as sparse representation.

Experiment: The proposed ML method was tested on five healthy volunteers. Data was acquired with golden angle radial trajectory under free-breathing on a 1.5T Philips scanner using a b-SSFP acquisition, (TR/TE=3/1.46 ms, matrix size: 160x160, FOV: 320 mm x 320 mm, slice thickness=8mm, scan duration ~ 20sec). An ECG gated breath-hold (BH) acquisition with similar parameters (scan duration ~10 sec) was performed as gold standard. The acceleration factor for both ML gated and ECG gated BH data was in the range of 2 to 3. To investigate the accuracy of the cardiac signal estimated with the proposed method, comparison to external ECG signal was done in all volunteers.

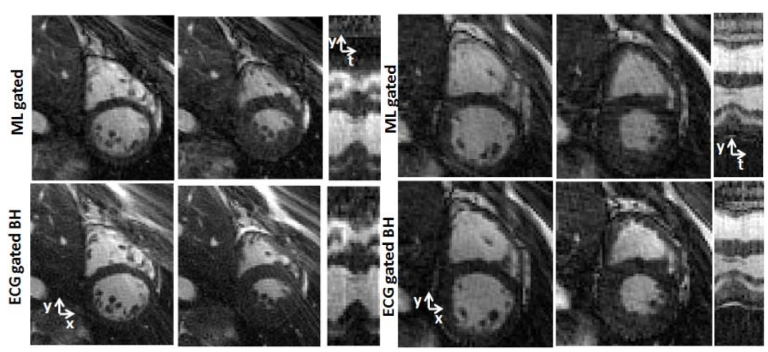

Fig. 2: Comparison of reconstructed CINE images using the proposed ML gated method from ECG-free free breathing data, and ECG gated breath hold (BH) acquisition for two volunteers. A temporal profile showing the variation of pixels across the heart is also shown.

Results: Using the estimated cardiac and respiratory signals, the ML gated reconstructed images in diastole and systole for two volunteers are shown in Fig. 2. The reconstructed images show spatial and temporal quality similar to the ECG gated breath-hold image reconstruction. The mean standard deviation of the delay between the R-peaks determined with external ECG and those estimated with proposed method was approximately 22 msec.

Discussion: A novel manifold learning based framework is proposed that can estimate accurate cardiac and respiratory gating signals from free breathing data and use these to achieve high spatial and temporal quality in retrospectively reconstructed CINE images. In comparison with existing self navigation respiratory gating and motion correction approaches[6,7], the proposed ML method does not require external ECG triggering for cardiac gating and can get both cardiac and respiratory gating signals from the acquired data. The proposed method has the potential to be applied with no restriction on image acquisition orientation. Due to its simplicity, the proposed method can be also easily integrated into existing motion correction frameworks. Further studies in patients will be performed to validate the proposed approach.

References: [1] Frauenrathet al, CMR,2010 [2] Belkin et al, MIT Press, 2001 [3] Wachinger et al, MedIA 2012 [4] Winkelmann et al, IEEE TMI, 2007 [5] Otazo et al. MRM 2010 [6] Hansen et al, MRM 2012 [7] Usman et al, MRM 2013