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Spatio-temporal motion correction and iterative reconstruction of in-utero fetal fMRI

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Objective

Unpredictable and excessive movement of fetuses have limited the clinical applicability of Resting-state functional Magnetic Resonance Imaging (fMRI). Previous studies have focused primarily on the accurate estimation of the motion parameters employing a single step 3D interpolation at each individual time frame to recover a motion-free 4D fMRI image. Here, we propose a novel technique based on four dimensional iterative reconstruction of the motion scattered fMRI slices.

Optimization Scheme

Assuming observed motion-contaminated image is: $\mathcal{T} \in \mathbb{R}^{B\times K\times H\times N}$

the desired motion-compensated image is: $\mathcal{X} \in \mathbb{R}^{\hat{B}\times\hat{K}\times\hat{H}\times N}$

and MR acquisition model as: $\mathbf{T}_n = DSM_n\mathbf{X}_n + z$

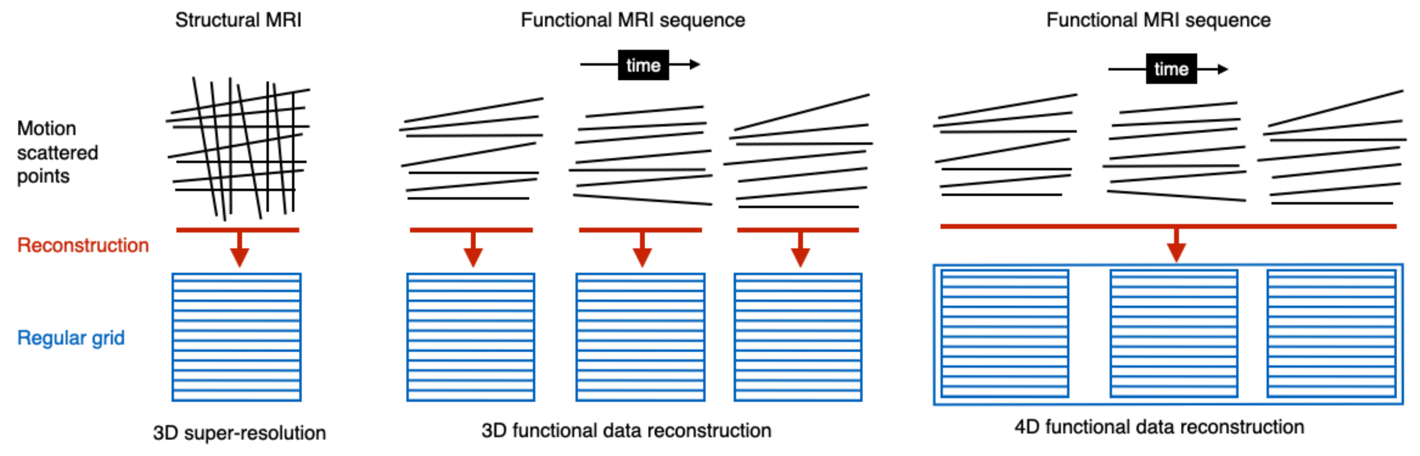
Our goal is to estimate the latent desired 4D image by minimizing the following cost function based on the inverse problem formulation:

$$\min_{\mathcal{X}} \sum_{n=1}^{N} \|DSM_n\mathbf{X}_n - \mathbf{T}_n\|^2 + \lambda\Re(\mathcal{X})$$

$$\min_{\mathcal{X}} \sum_{n=1}^{N} \|DSM_n\mathbf{X}_n - \mathbf{T}_n\|^2 + \lambda_{\text{rank}}\,\Re_{\text{rank}}(\mathcal{X}) + \lambda_{tv}\sum_{n=1}^{N}\Re_{tv}(\mathbf{X}_n)$$

$$\Re_{rank}(X) = \sum_{i=1}^{4}\alpha_i\|X_{(i)}\|_{tr} \qquad \Re_{tv}(X) = \sum_{n=1}^{N}\int|\nabla X_n|dxdydz$$

$$\min_{\mathcal{X},\{Y_i\}_{i=1}^4,\{U_i\}_{i=1}^4} \sum_{n=1}^{N}\|DSM_n\mathbf{X}_n - \mathbf{T}_n\|^2 + \lambda_{\text{rank}}\sum_{i=1}^{4}\alpha_i\left\|Y_{i(i)}\right\|_{tr} + \sum_{i=1}^{4}\frac{\rho}{2}\left(\|\mathcal{X}-Y_i+U_i\|^2 - \|U_i\|^2\right) + \lambda_{tv}\sum_{n=1}^{N}\int|\nabla\mathbf{X}_n|\,dbdkdh$$

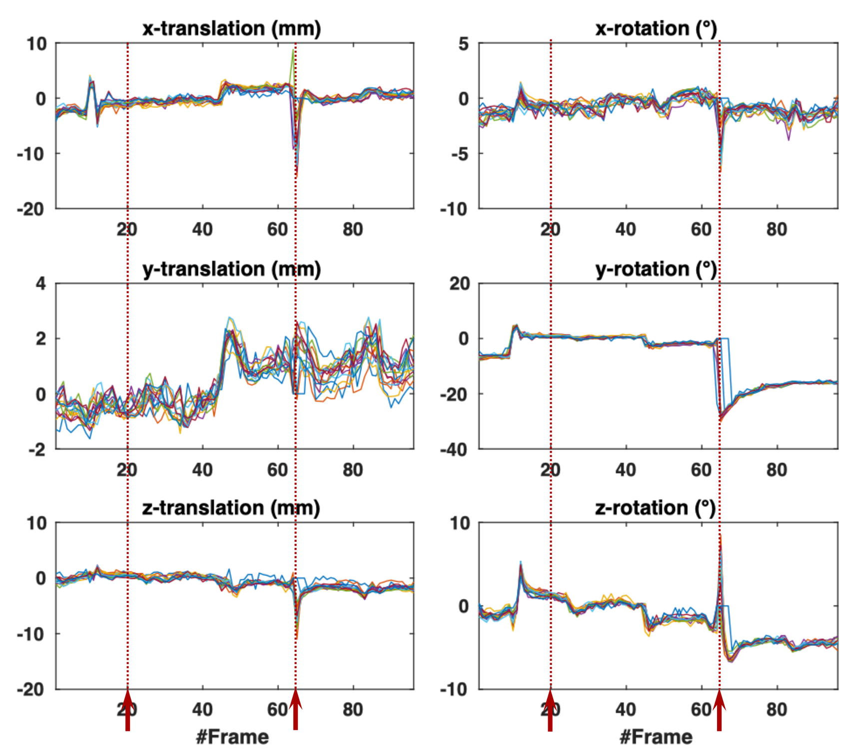


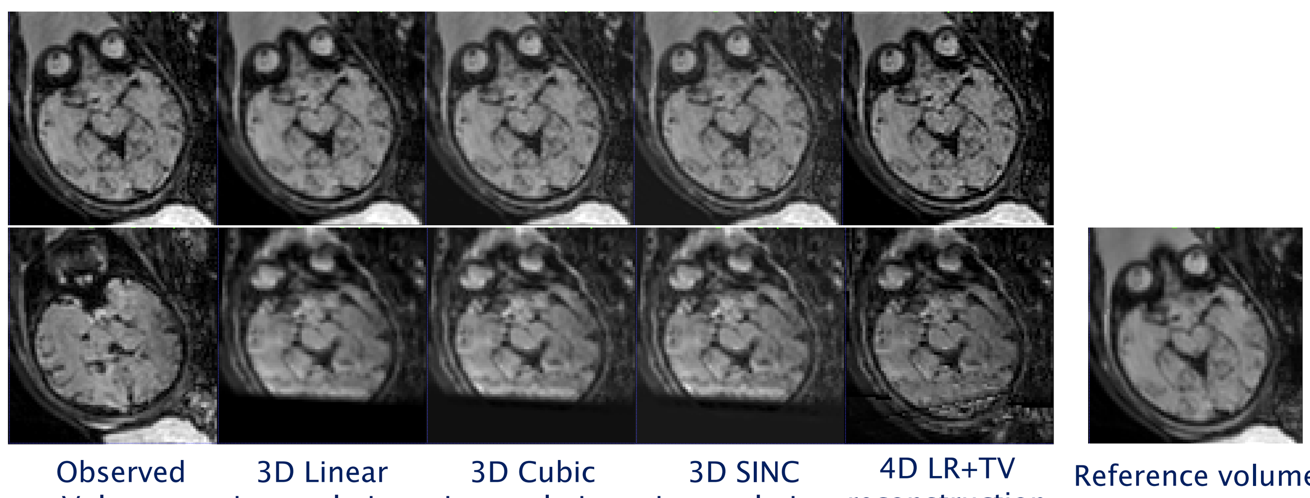
Over- sampling exists in case of 3D structural MRI (left panel), however, there is not enough data for separate reconstruction of each 3D fMRI volume (middle panel). Here we pro- pose to reconstruct the whole 4D fMRI at once using both spatial and temporal data structure (right panel).

Qualitative Results

When motion is small, all interpolation methods recovered a motion compensated volume, and our approach resulted in a **sharper image**.

In contrast, **with strong motion** relative to the reference volume, single step 3D interpolation methods are not able to recover the whole brain, and parts remain missing, whereas the proposed 4D iterative reconstruction did **recover the entire brain**.





Observed Volumes | 3D Linear interpolation | 3D Cubic interpolation | 3D SINC interpolation | 4D LR+TV reconstruction | Reference volume

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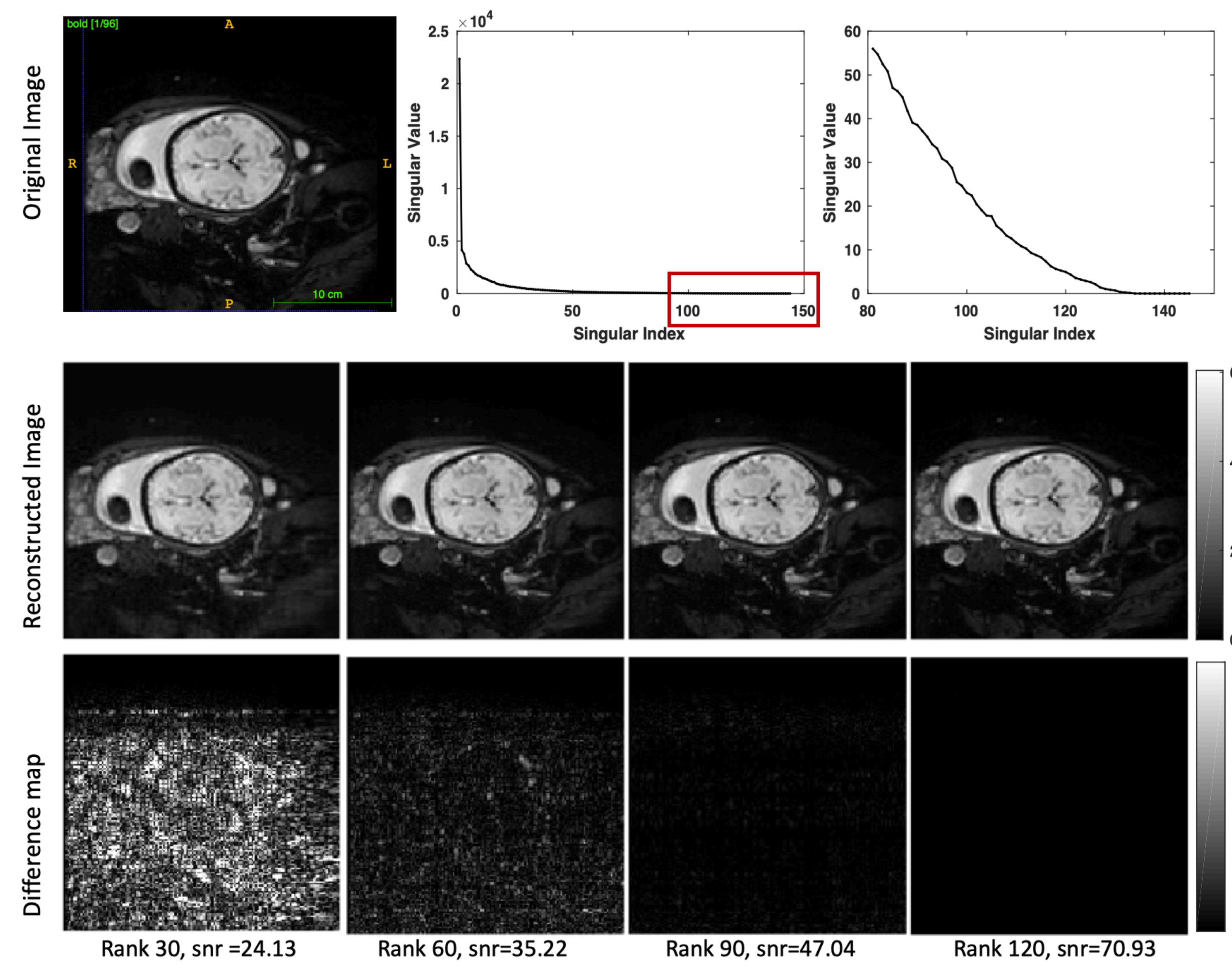
Low-rank Recovery

Low rank approximation of in-utero fMRI of a fetus with gestational age of 34w+4d. Top row shows the original slice, singular-value plot, and zoomed singular value plot of indices from 80 to 144. Bottom row shows the four reconstructed slices and their differences with the original image by using top 30, 60, 90, and 120 singular values, respectively.

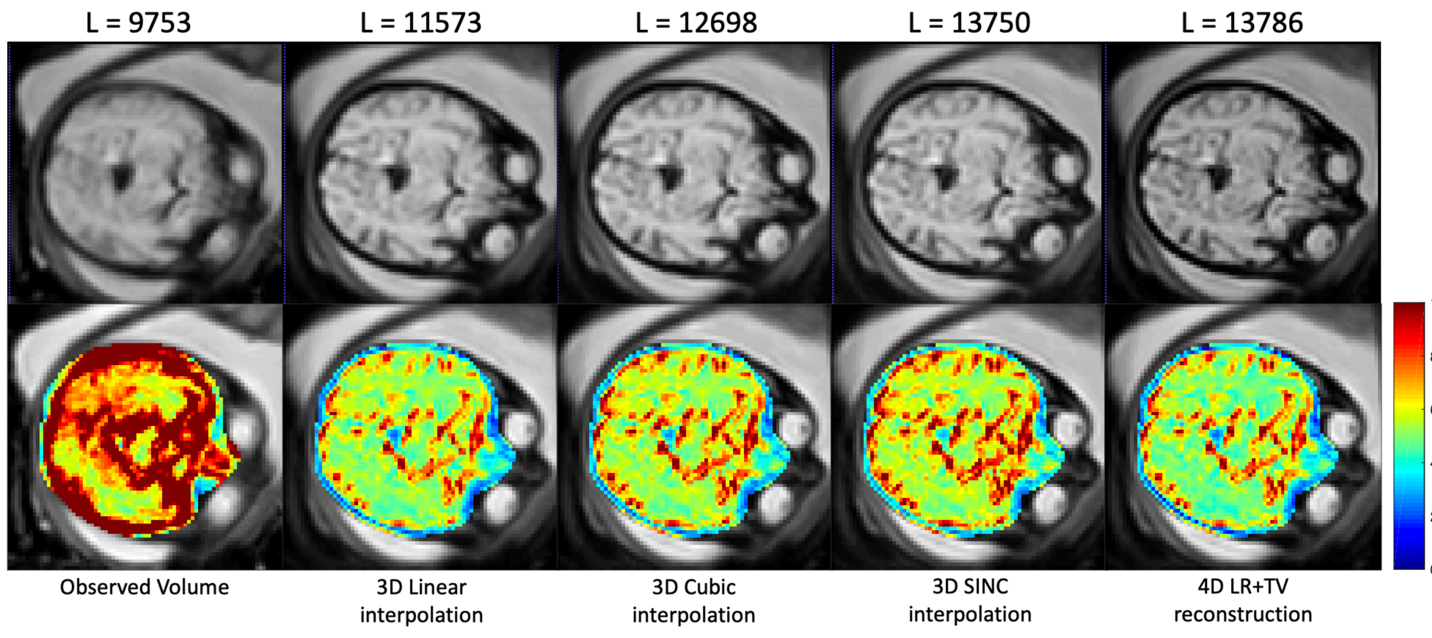
For the full 4D fMRI data of our cohort with the size of 144×144×18×96, four ranks, one for each unfolded matrix along one dimension is computed. Each is less than the largest image size 144. These ranks are relatively low in comparison to the total number of elements, implying in utero fMRI images could be represented using their low-rank approximations.



Quantitative Results

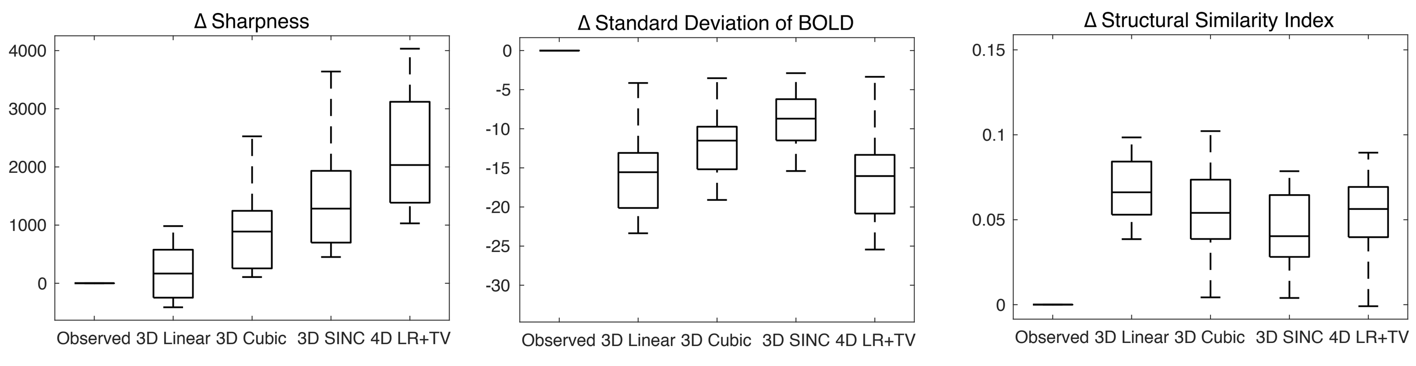
4D reconstruction achieves **sharper structural detail**, and overall **reduction of the standard deviation**, which is primarily related to motion.

Linear interpolation results in signals as smooth as the proposed method, **severe blurring** is observed in the obtained image by this approach.



The proposed method significantly ($p<0.01$, paired-sample t-tests for each comparison) outperforms all comparison methods in terms of **sharpness** and **standard deviation** of BOLD signal fluctuations.

The difference between linear interpolation and our approach **did not reach the statistical significance level for SSIM (p=0.28)**.



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