Trajectory Optimization in k-t GRAPPA

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Introduction: Dynamic imaging in MRI incorporates temporal correlation between frames. Spatial resolution can be increased by sharing or interpolating information between time frames. The practice can reduce temporal accuracy, however. Several reconstruction methods have been proposed to exploit temporal correlation, e.g., UNFOLD [1], TSENSE [2], k-t BLAST and k-t SENSE [3] and k-t GRAPPA [4]. The further choice of sampling pattern in k-t space affects SNR, unwrapping artifact, and temporal resolution. One desires the ability to optimize the sampling pattern given a priori knowledge of the image dynamics, such as breathing motion or contrast injection. Tsao J. *et al.* give the optimal sampling patterns for *k-t* BLAST and *k-t* SENSE by qualitatively analyzing the point spread function (PSF) in x-f space [5]. This paper focuses on the optimization strategy applied to k-t GRAPPA and conjectures a quantitative criterion for trajectory optimization. Parameters in the criterion can be adjusted to accommodate spatial and temporal scales of change.

Methods: k-t GRAPPA is a local spectrum interpolation strategy where the neighborhood correlations both in PE encoding dimension and temporal dimension are extracted. Missing k-space data points are estimated by convolution with a k-t kernel which is calibrated adaptively in time. Since the reconstruction is a second order statistics least square solution, the computational load is low. An example k-t trajectory is demonstrated in Fig. 1. We can see each periodic pattern is a square block of length equal to the acceleration factor R and the acquired data are on the main diagonal where all the off diagonal points are missing data ready to be estimated by the nearest neighbors in both k and t directions. In the k-t trajectories considered here, the t order of k column sampling in the block can be any permutation of {1, 2, … R}. The trajectory optimization problem is roughly compared between k-t SENSE and k-t GRAPPA. In k-t SENSE, the authors focused on point spread function such that positions containing large signals in x-f space overlap with positions containing small signals, in other words, the desired trajectory pattern should have the temporal filter effect. Thus the perspective of PSF constraining the sampling pattern in k-t space exhibits the explicit periodicity. The k-t GRAPPA method uses local interpolation and doesn't need the global x-f PSF analysis. Thus from the local interpolation point of view, the sampling pattern has a higher degree of freedom.

A criterion for evaluating sampling patterns posits that the temporal or spatial correlation is inversely proportional to the distance between data [5]. Thus the optimization is based on optimizing the overall distances from missing points to the known points due to k-t GRAPPA interpolation strategy in Fig. 1. Since the sampling pattern of size RxR is repeated along time and space, only one pattern is taken into consideration. Two criteria are proposed to judge the pattern selection:

1. For each missing data point inside the pattern, the average distance measure to all the neighboring known data is small.
2. For overall missing data points inside the pattern, the distance measure distribution tends to be uniform.

Criterion 1 means that the sampling pattern puts a missing data point as close to its neighboring known data as possible. Application of criterion (2) avoids the extreme case where some missing data points are close to its neighbors and are very well estimated while other points are far from neighbors and are poorly estimated. Therefore the reconstruction is constrained in balance by criterion 2. The average of L2 norm distance for all (R^2-R) missing points is a constant due to the periodicity of pattern and thus is an unsuitable measure. Therefore a criterion using inverse of L2 norm distance is proposed to evaluate the set of possible k-t trajectories:

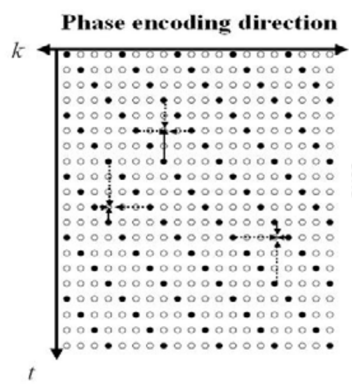

Fig. 1 k-t trajectory in k-t GRAPPA

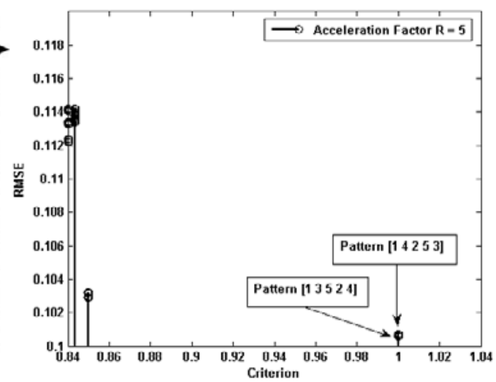

Fig. 2 k-t pattern comparison in k-t GRAPPA in R = 5 cardiac images

$$\max_{pattern} \sqrt[\alpha]{\frac{1}{(R^2-R)}\sum_{n=1}^{R^2-R}\frac{\left(\lambda_x\sum_k\frac{1}{d_n(k_x)}+\lambda_t\sum_k\frac{1}{d_n(k_t)}\right)^\alpha}{\max_{n=1,\cdots,R^2-R}\left(\lambda_x\sum_k\frac{1}{d_n(k_x)}+\lambda_t\sum_k\frac{1}{d_n(k_t)}\right)^\alpha}}$$

where λ_x and λ_t are the weighting factors in PE direction and temporal direction corresponding to the spatial and temporal correlations separately, α is the order of nonlinear transfer to adjust the distance distribution, $d_n(\cdot)$ defines the Euclidean distance from missing data n to its nearest neighbors, k_x and k_t represents coordinates in PE direction and temporal direction respectively.

Results and Discussion: Cardiac data was acquired using Siemens 8-channel cardiac array on 3T scanner (TR=2; TI=100; TE=1.27; FOV=251x189; Flip Angle=12; Slice thickness=8mm; matrix 192x88). The 70 fully acquired frames are decimated by different patterns in acceleration factor of R=4, R=5 where 20 ACS lines are retained. Image sets are reconstructed by k-t GRAPPA and compared to the fully sampled result to derive a RMSE (Root Mean-Square-Error) for the pattern. Table 1 demonstrates the case R=4, where the optimal trajectories according to the optimization criterion ($\lambda_x = \lambda_t = 1, \alpha = 2$ for R=4,5) produce the lowest RMSE. Patterns [1,2,3,4] and [1,4,3,2] have the highest criterion value. In the R=5 case the trajectory optimization criterion predicts optimal patterns of [1 3 5 2 4] and [1 4 2 5 3], corresponding with the lowest RMSE values of 10.06% and 10.07% shown in Fig. 2.

[k,t]pattern	[1,2,3,4]	[1,2,4,3]	[1,3,2,4]	[1,3,4,2]	[1,4,2,3]	[1,4,3,2]
RMSE	9.59%	10.49%	10.44%	10.45%	10.5%	9.56%
Criterion	0.9242	0.9186	0.9186	0.9186	0.9186	0.9242

Table 1. k-t pattern comparison in k-t GRAPPA in reduction factor 4 cardiac images

Conclusions: The experimental results show that the proposed criterion provided the correct guidance for trajectory optimization. k-t trajectory optimization is a reconstruction method dependent and object dependent problem. This abstract focuses this issue on k-t GRAPPA method and proposes a pattern searching criterion based on the inverse of an Euclidean distance measure. The object dependence corresponds to different spatiotemporal correlations, which are adjusted by λ_x and λ_t in the criterion. Future work will study the choice of these parameters in image sets with varying temporal character, such as cardiac cine images and contrast uptake studies.

References:

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