Technique for Reconstruction based on Intensity Order (TRIO) applied as a second stage for dynamic MRI reconstruction.

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INTRODUCTION. Long acquisition times are still a limitation for many applications of MRI, especially in 3D and dynamic imaging. Many undersampling reconstruction techniques have been proposed to overcome this problem. These techniques are based on acquiring less samples of the k-space and estimating the non-acquired data by using prior or extra information [1-6]. Recently we proposed a technique to reconstruct under-sampled data using an estimation of the sorted image-domain (Ω-domain) [7]. We define Ω as the set of order relations which sort the pixels from brightest to darkest, so that the image is transformed into a monotonic smooth curve. Our Technique for Reconstruction based on Intensity Order (TRIO) consists in looking for an image that satisfies Ω and matches the acquired samples of *k*-space. The hypothesis are that we can recover the non-acquired data using a good estimation of Ω and that Ω can be estimated reasonably well from low-resolution images, adjacent slices in volumetric images or temporal correlation in dynamic sequences. We showed that TRIO can effectively reconstruct 2D-cine (under-sampling factor $Q=4$), estimating correctly the temporal evolution of the objects. In this work, we show that TRIO can be used as a second stage reconstruction by using other algorithms to estimate Ω, so that the images are improved even further (as measured by the RMSE). We also studied how the quality of reconstruction is affected by taking the order information from a distorted image. Results show that the accuracy of TRIO reconstruction is dependent of the order estimation; however independently of the estimation used, TRIO as a second stage reconstruction improves the quality of the conventional reconstructions.

METHOD. TRIO is an l_2-optimization that maximizes data consistency, subject to the order relations Ω:

$$Min\sum\left\|W^{H}UWP^{T}s-y\right\|^{2}\qquad S.t.\ \forall i>j, s_i \geq s_j \qquad \text{(Eq.1)}$$

Where $\boldsymbol{x} = \boldsymbol{P}^T\boldsymbol{s}$ is a dynamic frame for time t; $\boldsymbol{P}$ a permutation matrix constructed from Ω; $\boldsymbol{s}$, the sorted version of $\boldsymbol{x}$; **W**, the Fourier transform; $\boldsymbol{U}$, the under-sampling pattern and $\boldsymbol{y}$, the acquired aliased data. As TRIO only needs an estimation of $\boldsymbol{P}$, we can relax the constraints (Eq.1), by creating N/n disjoint groups (α_k) of n pixels each, and defining the relations between every two groups:

$$Min\sum\left\|W^{H}UWP^{T}s-y\right\|^{2} \qquad \text{(Eq.2)}$$

$$S.t.\forall(s_i \in \alpha_k),(s_j \in \alpha_{k+1}): s_i \geq s_j, \forall\, 1 \leq k \leq N/n$$

TRIO was applied to 2D-cine data, (Philips Intera 1.5T, B-FFE, 128x128x48, 1.56x2.08mm^2 resolution, TR/TE=3/1.46 ms). The raw data was undersampled retrospectively by employing a pseudo-random undersampling pattern (random in the phase encoding direction and uniform in time) with a factor of *4*. The reconstruction was done independently for each line in the phase encoding direction. When using TRIO as a second stage, the reconstructions achieved by the first stage were used to obtain the order Ω. To test the method's robustness to wrong order estimations, a T2W-TSE image (Philips Intera 1.5T, 256x256, 0.9x0.9mm^2 resolution, TR/TE=4438/100 ms) was reconstructed with different sources for Ω. The estimated Ω was obtained from distorting the original image in two fashions: adding zero-mean Gaussian noise with a standard deviation from 0 to 10%; and by progressively blurring the image with a Gaussian point spread function of widths from 0 to 1.5 pixels. In both cases reconstructions were done using a group size (n) of 4 and 8.

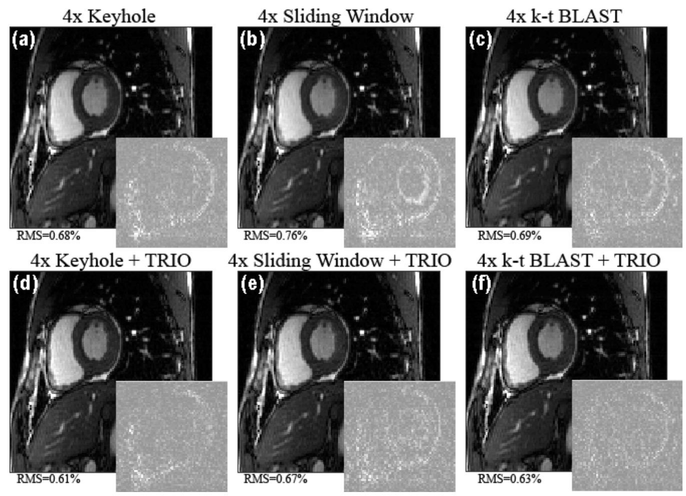

Fig. 1 (a) 4x Keyhole (b) 4x Sliding window (c) 4x k-t BLAST (d) 4x TRIO, Ω from Keyhole (e) 4x TRIO, Ω from Sliding Window (f) 4x TRIO, Ω from k-t

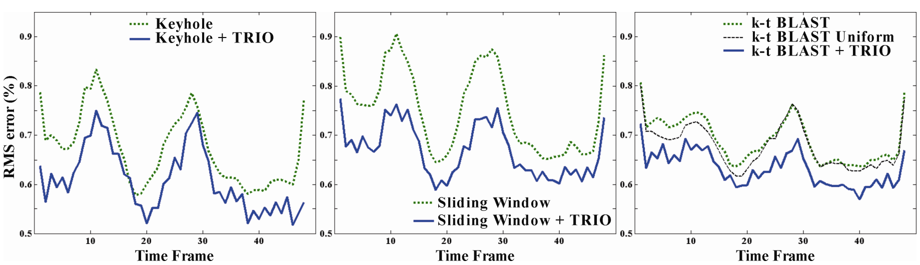

Fig. 2. RMS errors as a function of time for TRIO with intensity order estimated from Keyhole, k-t BLAST and Sliding Window, compared against the first reconstructions

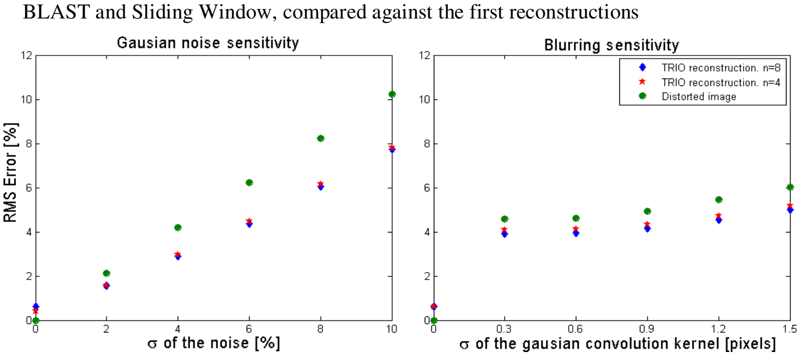

Fig. 3. RMS errors for a distorted image used to estimate Ω and TRIO reconstructions using that order information. All values compared to the fully

RESULTS. The dynamic sequence reconstructions are shown in Fig. 1. TRIO applied as a second stage reduced the root mean square (RMS) error from *0.68%* (using Keyhole) to *0.61%*, from *0.69%* (using k-t BLAST) to *0.63%*, and from *0.76%* (using SW) to *0.67%* as compared to the fully sampled image. TRIO improvements as a function of time, when used as a second stage, are shown in Fig.2, where we also included k-t BLAST with a uniform under-sampling pattern. Additionally, as can be seen in Fig. 3 TRIO is able to reduce the RMS error from all distorted images, although the final reconstruction is highly dependant on the quality of the order information Ω. As shown in the graph, the RMS error increases linearly with the noise and increases little with the blurring, after an important increase for a very small blurring. The group size n does not make a significant difference, but a larger group size produces a minor improvement when some distortion is applied.

CONCLUSION. We have presented an application of the reconstruction algorithm TRIO as a second stage. Since the mechanisms of reconstruction are different, TRIO can use the images reconstructed in the first stage as order information. The method was able to improve the reconstructions made by Keyhole, Sliding Window and k-t BLAST. We also showed how the estimation error increases as the image from where the order is obtained is degraded, thus affecting TRIO reconstruction. As expected the TRIO reconstruction always improves the image quality as compared to the degraded one

References: [1] van Vaals et al. JMRI 3,4 (1993); [2] Jones et al.MRM 29,6 (1993); [3] Tsao et al. MRM 50,5 (2003); [4] Madore et al.MRM 42,5 (1999); [5] d'Arcy et al. NMR 15 (2002); [6] Irarrazaval et al. MRM 54,5 (2005); [7] ESMRMB 2008 pp.