Reduced Blurring in 3D Fast Spin Echo through Joint Temporal ESPIRiT Reconstruction

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Introduction: Volumetric (3D) Fast Spin Echo (FSE) is an attractive alternative to 2D FSE as it provides isotropic resolution. However, long echo trains are required to maintain scan efficiency, leading to blurring due to T2 decay [1]. Flip-angle modulation can reduce this effect [2], but blurring often persists, particularly in musculoskeletal applications. In this work, we aim to reduce blurring by modeling the signal's temporal behavior. By constraining the temporal decay to a low-dimensional subspace as in [3] and by randomizing the echo train ordering as in [4], we are able to reduce blurring without explicitly estimating a T2-relaxation map. This approach combines ESPIRiT [5], a parallel imaging (PI) and compressed sensing (CS) method, with joint-thresholding of the temporal image coefficients to reconstruct a full time series of images. This differs from other approaches where CS and PI are combined in a parametric framework with the end goal of tissue quantification [3, 4, 6-9].

Theory: Traditional 3D FSE reconstruction neglects the echo train time progression and a single image is reconstructed. In contrast, here we assume the data represent a time series of images corresponding to each echo time in the echo train. Implicitly, 3D FSE undersamples this *k-t* space by at least a factor of the echo train length. However, the temporal behavior is well-approximated by a low-dimensional subspace [3, 6]. The relaxed forward model is then $y = E\Phi\Phi^T x$, where x is the time series of images, Φ is a pre-determined temporal basis, and E is the PI encoding operator [5]. Defining the image temporal coefficients as $\alpha := \Phi^T x$, this new approach solves $\min_\alpha \|y - E\Phi\alpha\|_2^2 + \lambda\|\Psi\alpha\|_1$ where Ψ is a spatial wavelet operator. The time series is then computed as $x = \Phi\alpha$. In contrast to [3], the wavelet coefficients of α at a particular voxel are jointly soft thresholded since they represent the same T2 value. This model enables sampling *k-t* space in an arbitrary fashion [4, 10]. Fig. 1 illustrates the typical center-out phase-encode ordering for accelerated proton-density Cartesian 3D FSE compared to a uniform random ordering. The center-out pattern leads to a blurring point spread function, while the random pattern spreads artifacts incoherently through space and time.

Methods: A human foot was acquired with a fully sampled 2D multi-echo sequence (TR/TE = 3060/10 ms, 32 echoes, 32 coils), and retrospectively (under) sampled in time as illustrated by Fig. 1. This simulates 3D FSE with an acceleration factor of 1 (32 in *k-t* space). Additionally, a human knee was scanned with 3D FSE (TR/TE = 1600/6 ms, 50 echoes, 8 coils) with a uniform density Poisson acceleration of 1.8 (90 in *k-t* space) with center-out and random echo ordering. An ensemble of 300 flip-angle modulated decay curves with T2 values between 20 ms and 400 ms were Bloch-simulated; the temporal basis Φ consisted of the principle components [8] of this ensemble. The data were reconstructed with both ESPIRiT and the proposed method (ESPIRiT+T) using $K \in \{1,2,3\}$ elements from Φ.

FIG. 1

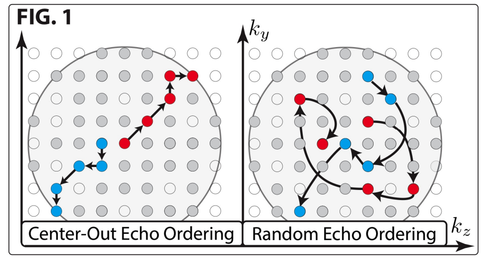


FIG. 2

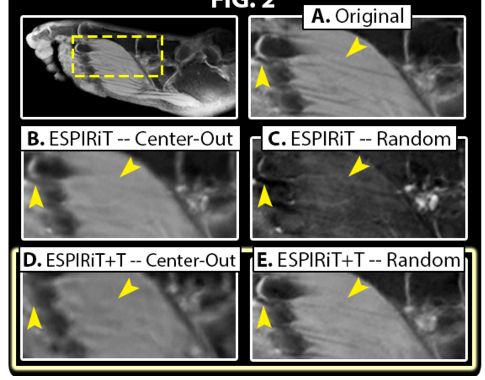


FIG. 3

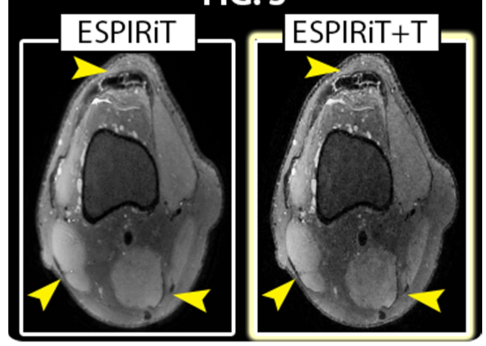
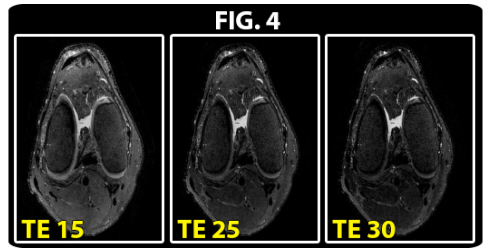


FIG. 4



Results and Discussion: Fig. 2 compares the first TE of the fully sampled feet to ESPIRiT and ESPIRiT+T for $K = 3$. Fig. 2B is equivalent to traditional 3D FSE, and suffers from T2 blurring. Incoherent artifacts and mixed contrast are seen in Fig. 2C due to the random echo ordering. The increased blurring seen in Fig. 2D is likely due to the poor conditioning from the center-out echo ordering, while Fig. 2E (random echo ordering) is sharper and has similar image quality to that of Fig. 2A. Fig. 3 compares the reconstruction on the knees using ESPIRiT (center-out ordering) to the first echo of the proposed method (random ordering, fully sampled center) for $K = 2$. The new approach reduces blurring and emphasizes structure. Note that for $K = 1$, the method is equivalent to high pass filtering with the "average" T2 value with wavelet denoising [11]. Fig. 4 shows later echo times reconstructed by the proposed method, which are T2-weighted.

Conclusion: The proposed reconstruction in tandem with randomized view ordering is promising for reducing blurring in 3D FSE.

References: **[1]** Tariq, ISMRM 21,1664, 2013. **[2]** Busse, MRM, 2006; 60:640-49. **[3]** Huang, MRM, 2012; 67:1355-66. **[4]** Doneva, MRM, 2010; 64:1114-20. **[5]** Uecker, MRM, 2013, doi:10.1002/mrm.24751. **[6]** Pedersen, MRM, 2009; 62:706-16. **[7]** Velikina, MRM, 2013; 70:1263-73. **[8]** Huang, MRM, 2013; 70:1026-37. **[9]** Ma, Nature, 2013; 495:187-92. **[10]** Zhao, IEEE TMI, 2012; 31:1809-20. **[11]** Cukur, IEEE TMI, 2011; 30:1017-27.