T2 Shuffling: Multicontrast 3D Fast Spin Echo Imaging

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Introduction: Fast Spin Echo (FSE) sequences are the workhorse of MR imaging due to their speed and robustness to image artifacts. However, due to T2 decay, the reconstructed image suffers from blurring which grows with increasing echo train length (ETL) [1]. These drawbacks hinder the use of 3D FSE for musculoskeletal imaging, as the image quality attainable in the allotted scan time is not clinically acceptable [1, 2]. We previously showed that by modeling the temporal aspect of the acquisition, we could reduce image blurring and recover a full time series of images at different virtual echo times [3]. However, the previous approach did not leverage full scan efficiency due to limitations in the pulse sequence design. Additionally, the reconstructed images suffered from residual artifacts at high acceleration factors. Here, we address these limitations with T2 Shuffling, an extension of our subspace method [3], where we randomly shuffle the echo train view ordering during acquisition and constrain the temporal behavior during reconstruction.

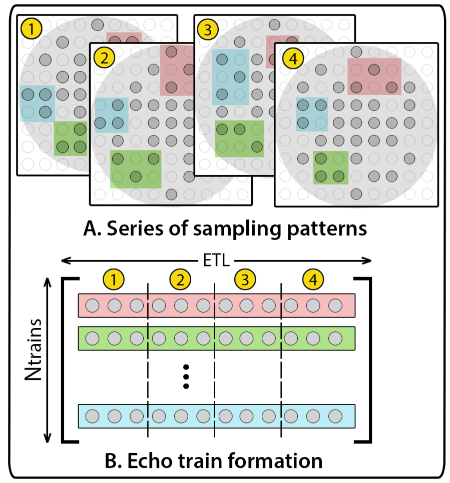

Fig 1. A series of sampling patterns are generated for batches of echo times. Nearby echoes in each batch are randomly ordered to form echo trains.

Improved Pulse Sequence Design: We modified the CUBE 3D FSE pulse sequence (GE Healthcare) to sample and store arbitrary phase encodes at arbitrary ETLs. This is used to resample phase encodes at different echo times, enabling variable-density sampling in *k-t* space. Fig. 1 shows the echo train view-ordering scheme. A series of undersampled variable density Poisson-disc sampling patterns are generated for batches of echo times. To reduce eddy current effects, echo trains are formed by grouping phase encodes locally in each batch and then randomizing their order. Scan efficiency is improved by increasing the ETL and acquiring more data in the same scan time.

Reconstruction Algorithm: The T2 Shuffling reconstruction builds off of [3]. The forward model is $y = Ex$, where x is the time series of images and E is the ESPIRiT encoding operator [7]. The signal is approximated by $x = \Phi\alpha$, where Φ is a pre-determined temporal basis of dimension K and α are the temporal image coefficients [3-5]. The reconstruction solves $\min_\alpha \|y - E\Phi\alpha\|_2^2 + R(\alpha)$, where $R(\alpha)$ is a locally low rank (LLR) operator on the temporal image coefficients [6]. The LLR regularization further exploits spatial correlations in the temporal coefficients, providing substantial dimensionality reduction beyond the capabilities of joint wavelet regularization [3, 5].

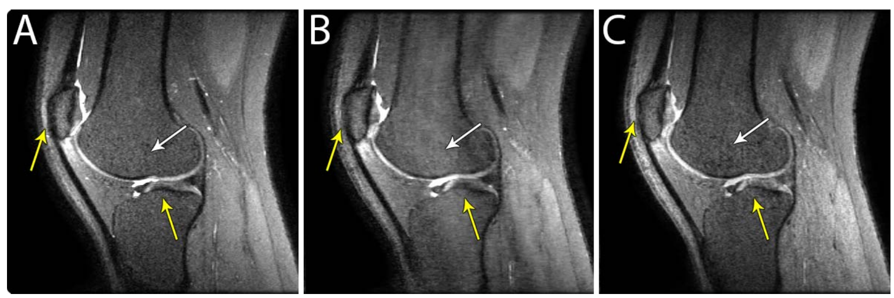

Fig 2. (A) Conventional ESPIRiT reconstruction leads to image blur (yellow arrows). (B) ESPIRiT+T models the temporal decay but residual artifacts persist (white arrow). (C) T2 Shuffling increases image sharpness.

Experiments: A volunteer's knee was scanned using the modified CUBE pulse sequence (TR/TE = 1400/5 ms, 8 coils). The first scan used a center-out view ordering [1] with an ETL of 37 and variable-density Poisson disc acceleration of 4.6 for a total scan time of 6 minutes. The second and third scans used a randomized view ordering with ETLs of 50 and 80, respectively. To maintain the same scan time, acceleration factors were adjusted to 3.24 and 1.95 for the second and third scans, respectively. The first scan was reconstructed into a single proton-density image. The second scan was reconstructed ($K = 3$ temporal coefficients) into 50 virtual echo time images using the method in [3], and the third scan was reconstructed into 80 virtual echo time images as outlined above.

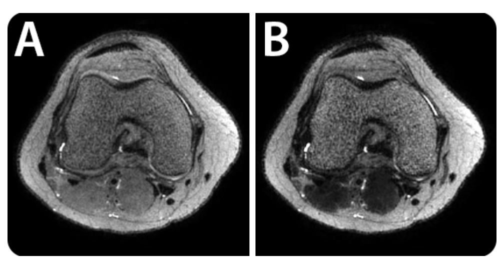

Fig 3. T2 Shuffling images at virtual echo times of (A) 90 ms and (B) 200 ms.

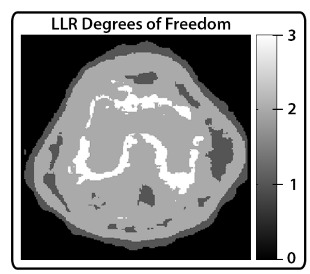

Fig 4. LLR reduces the degrees of freedom within the subspace

Results and Discussion: The reconstructions were implemented using the Berkeley Advanced Recon Toolbox [8]. Fig. 2 shows the reconstruction of the first scan with ESPIRiT [7], a parallel imaging and compressed sensing method that does not compensate for signal decay, and compares it to the reconstructions of the second scan using ESPIRiT+T [3] and the third scan using T2 Shuffling at comparable virtual echo times. Fig. 3 shows the T2 Shuffling reconstruction at later virtual echoes. T2 Shuffling provides increased image sharpness and multiple image contrasts at the same scan time, effectively trading off longer ETLs for lower g-factors. The dimensionality reduction offered by LLR is seen in Fig 4; the degrees of freedom at most voxels are reduced below $K = 3$.

Conclusion: T2 Shuffling improves scan efficiency, enabling multi-contrast 3D FSE at clinically feasible scan times.

References: **[1]** Busse, MRM, 2008; 60:640-49. **[2]** Tariq, ISMRM 21,1664, 2013. **[3]** Tamir, ISMRM 22, 0616, 2014. **[4]** Huang, MRM, 2013; 70:1026-37. **[5]** Zhao, MRM, 2014, doi:1010.1002/mrm.2542. **[6]** Zhang, JMRI, 2013, doi:10.1002/jmri.24551. **[7]** Uecker, MRM, 2014; 71:990-1001. **[8]** bart: 10.5281/zenodo.12495.