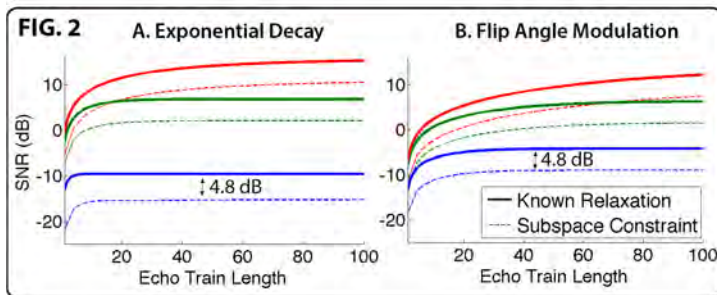
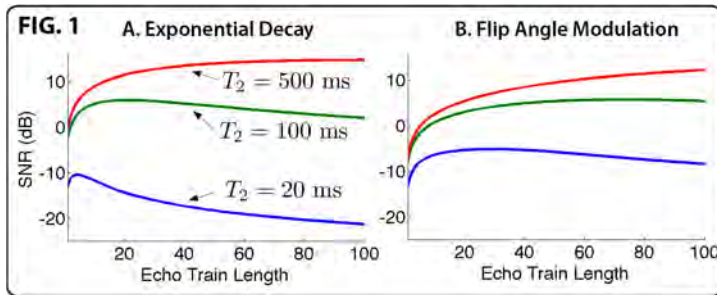


Improved Scan Efficiency of 3D Fast Spin Echo with Subspace-Constrained Reconstruction

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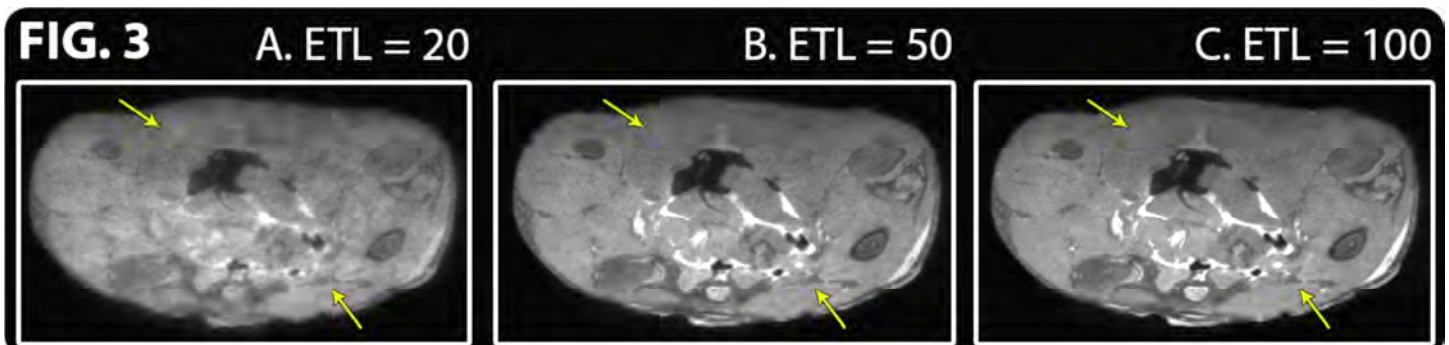
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Introduction: Scan efficiency plays a critical role in Fast Spin Echo (FSE) imaging because of the long TR intervals necessary to achieve the desired image contrast. Given a fixed scan-time budget, there are a finite number of TR intervals to collect echo trains, and this number is independent of the echo train length (ETL). However, in conventional reconstruction, long ETLs cause image blurring and mixed contrast due to uncompensated signal decay [1-3]. Model-based approaches that account for signal decay can overcome this limitation [4-8], but the impact of ETL is unclear when operating in an undersampled regime. In this work, we explore the utility of using a subspace-constrained reconstruction to increase ETLs without increasing noise or image blurring [7]. We show the approach has a fixed SNR cost, independent of ETL, compared to a reconstruction endowed with perfect knowledge of relaxation.



Theory and Simulations: Without accounting for signal decay, the ETL can be extended to acquire new or average additional phase encode lines. However, as Fig. 1 shows, the SNR does not monotonically increase due to noise, and the optimal ETL is relaxation dependent. This holds true for mono-exponential decay as well as decay from variable flip-angle modulation [1]. When the relaxation parameters are known, additional echoes can be optimally combined to improve SNR up to diminishing returns. Fig. 2 shows the resulting SNR as a function of ETL for the optimal combination. In a subspace model, in which relaxation is unknown, the signal is instead approximated by $x = \Phi\alpha$, where x is the time-series of images during the ETL, Φ is a truncated orthonormal basis of dimension K , and α are the K temporal image coefficients [6-8]. Because of the subspace constraint, the variance of the total noise in the system is $K\sigma^2$, independent of ETL. Fig. 2 shows this fixed SNR cost compared to the optimal solution (4.8 dB for $K = 3$). Thus if the model error $\|x - \Phi\alpha\|$ is small, it is beneficial to increase the ETL. This benefit may also hold in general for other model-based reconstructions.

Experiments: We modified the CUBE 3D FSE pulse sequence (GE Healthcare) to support randomized view ordering over arbitrary ETLs. A chicken phantom was scanned with TR/TE = 1500/6 ms and an 8-channel head coil. A 6 minute and 30 second scan time allowed for 260 TR intervals. The scan used a variable flip-angle modulation scheme [1] with an ETL of 100 and variable density Poisson disc acceleration factor of 1.57. The ETL was chosen to reduce g-factor effects and leave sufficient time for longitudinal magnetization recovery. The data were reconstructed into a time-series of images using the method proposed in [7]. The reconstruction combines ESPIRiT [9], a compressed sensing and parallel imaging method, together with the temporal subspace constraint. The basis Φ was generated using principal component analysis ($K = 3$) on an ensemble of simulated signal evolutions [6, 7, 10]. To test the usefulness of the long ETL, reconstructions were performed using the data from (A) the first 20 echoes, (B) 50 echoes, and (C) all 100 echoes. The reconstructions were implemented using the Berkeley Advanced Recon Toolbox [11].



Results and Discussion: Fig. 3 shows the reconstructions of the 8th virtual echo image, which corresponds to an echo time of 63 ms. Although all images have similar sharpness, the image in (A) suffers from residual aliasing artifacts due to the short ETL. The reconstruction in (B) leverages the additional data to improve image quality, and (C) shows marginal improvement due to the longer ETL, which is in agreement with Fig. 2. There is a clear benefit to using data at later echo times to improve the reconstruction.

Conclusion: Subspace-constrained reconstruction can be used to increase scan efficiency of 3D FSE using very long ETLs.

References: [1] Busse, MRM, 2008; 60:640-49. [2] Busse, MRM, 2004; 51:1031-37. [3] Tariq, ISMRM 21,1664, 2013. [4] Block, IEEE TMI, 2009; 28: 1759-69. [5] Sumpf, JMRI, 2011; 34:420-28. [6] Huang, MRM, 2013; 70:1026-37. [7] Tamir, ISMRM 22, 0616, 2014. [8] Zhang, JMRI, 2013; doi: 10.1002/jmri.24551. [9] Uecker, MRM, 2014; 71:990-1001. [10] Ben-Eliezer, MRM, 2014; doi: 10.1002/mrm.25156. BART (2014), doi: 10.5281/zenodo.12495.