High Speed 3D Overhauser-Enhanced MRI using combined b-SSFP and Compressed Sensing

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Motivation

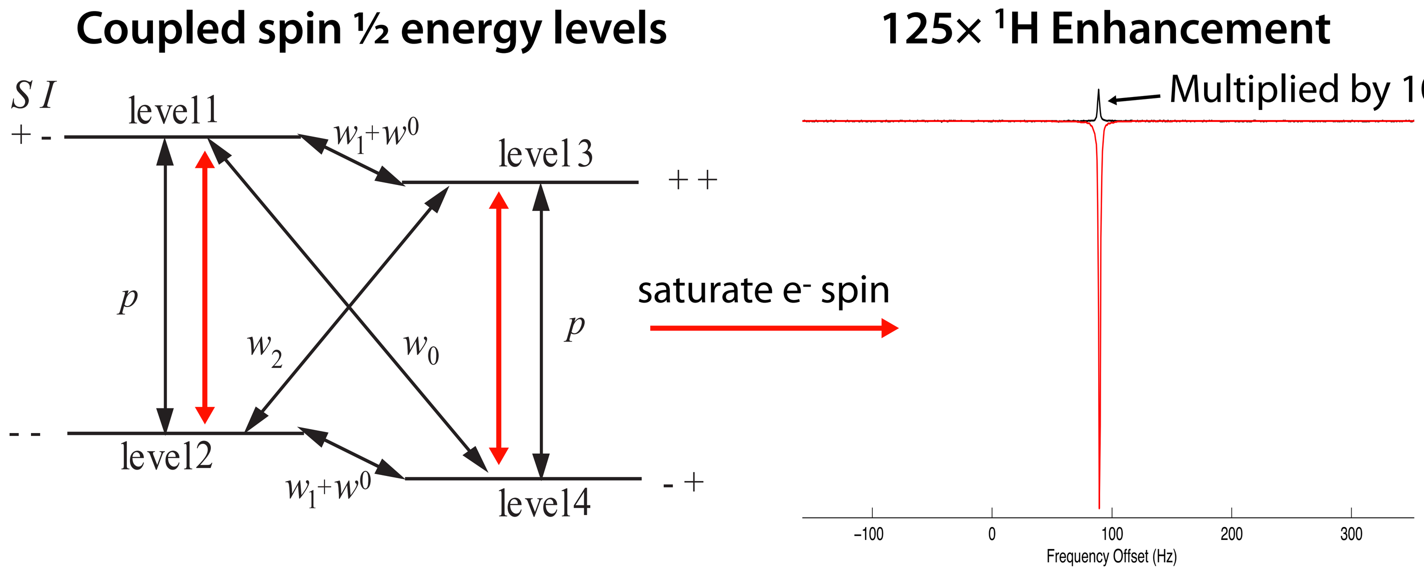
Nitroxide radicals have been proposed for several biomedical applications such as monitoring the oxidative stress of tissues, radioprotection, and as a neuroprotector following stroke. Free radicals have also been implemented in secondary brain injuries during reperfusion. Consequently, there is much interest in imaging free radicals in vivo to determine their role in these biological processes.

Using the Overhauser effect to transfer the e- spin polarization to coupled ^{1}H nuclei we have developed a new b-SSFP sequence to image the presence of free radicals with greater temporal resolution than previously reported [1].

The Overhauser Effect

The e$^-$ spin of a nitroxide free radical is strongly coupled to the ^{1}H nuclear spins of nearby water molecules. Saturation of the e$^-$ spin resonance can transfer part of the 660X larger e$^-$ spin polarization to ^{1}H nuclear spin polarization.

Coupled spin ½ energy levels **125× ^{1}H Enhancement**



The Signal enhancement given by [2]:

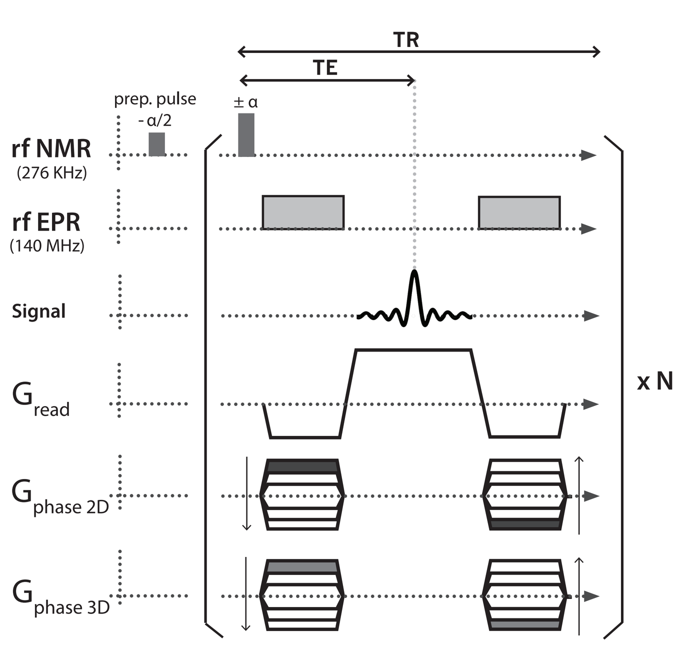
$$\frac{\langle I_z\rangle}{\langle I_0\rangle} = E = 1-\rho f s\frac{|\gamma_S|}{\gamma_I}$$

- ρ is dependent on the local dynamics between the two spins.
- f accounts for 1H relaxation not due to coupling to the electron
- s describes the saturation of e- spin and depends on the applied EPR power

$$\rho = \frac{w_2 - w_0}{w_0 + 2w_1 + w_2}$$

$$f = 1-\frac{T_1}{T_{10}} \qquad s = \frac{AP}{1+BP}$$

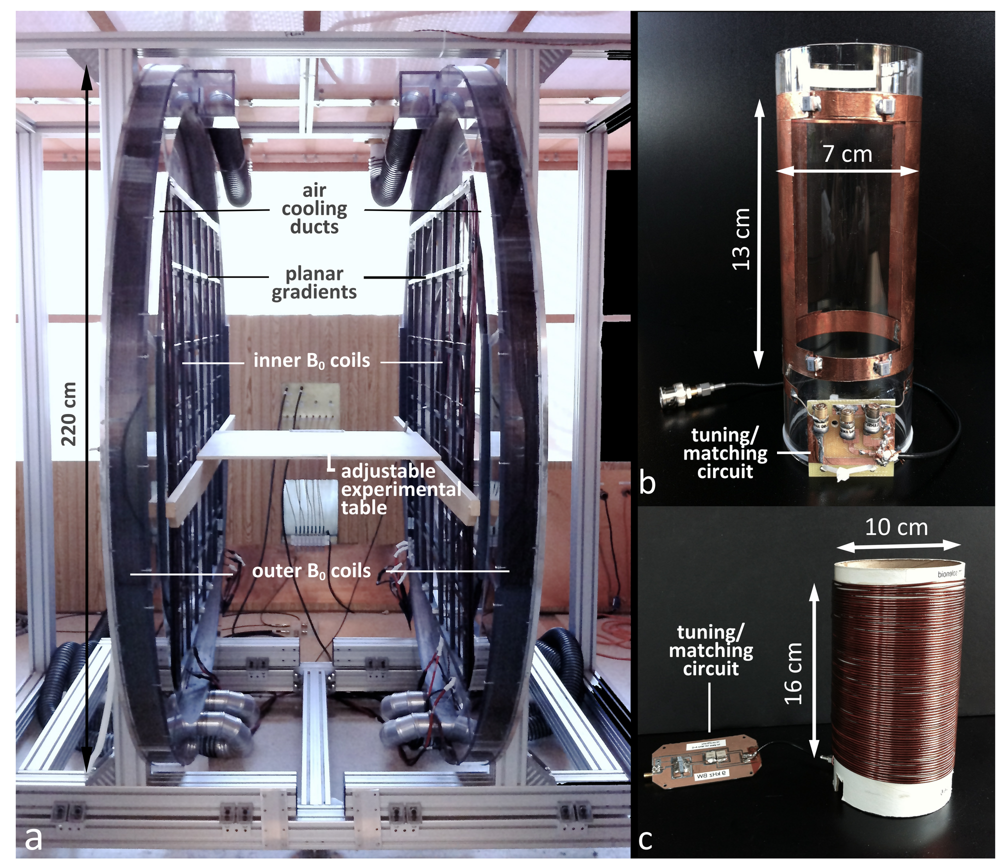
New Overhauser b-SSFP Sequence



b-SSFP sequence with EPR irradiation during the phase encode gradients. TR/TE = 54/27 ms. Sample T1/T2 = 540 /490 ms.

Unlike all OMRI sequences in the literature, we embed the EPR saturation step with the phase encode gradients. ***This adds no extra time to the sequence!*** Other OMRI sequences use a separate irradiation step of ~ T1 of the nucleus that is reapplied every T1. This extra step is eliminated, saving ~ 2 min. acquisition time for the sample and sequence parameters used here.

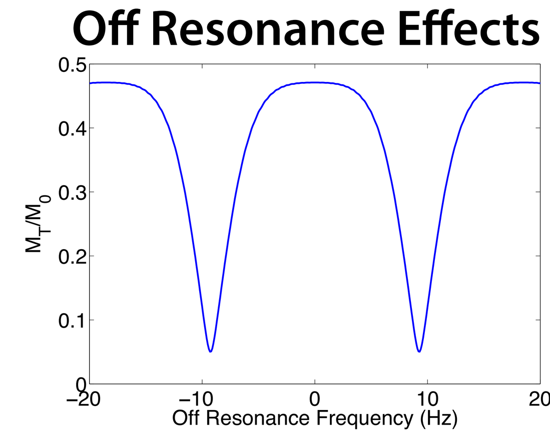
The Low Field Imaging Lab



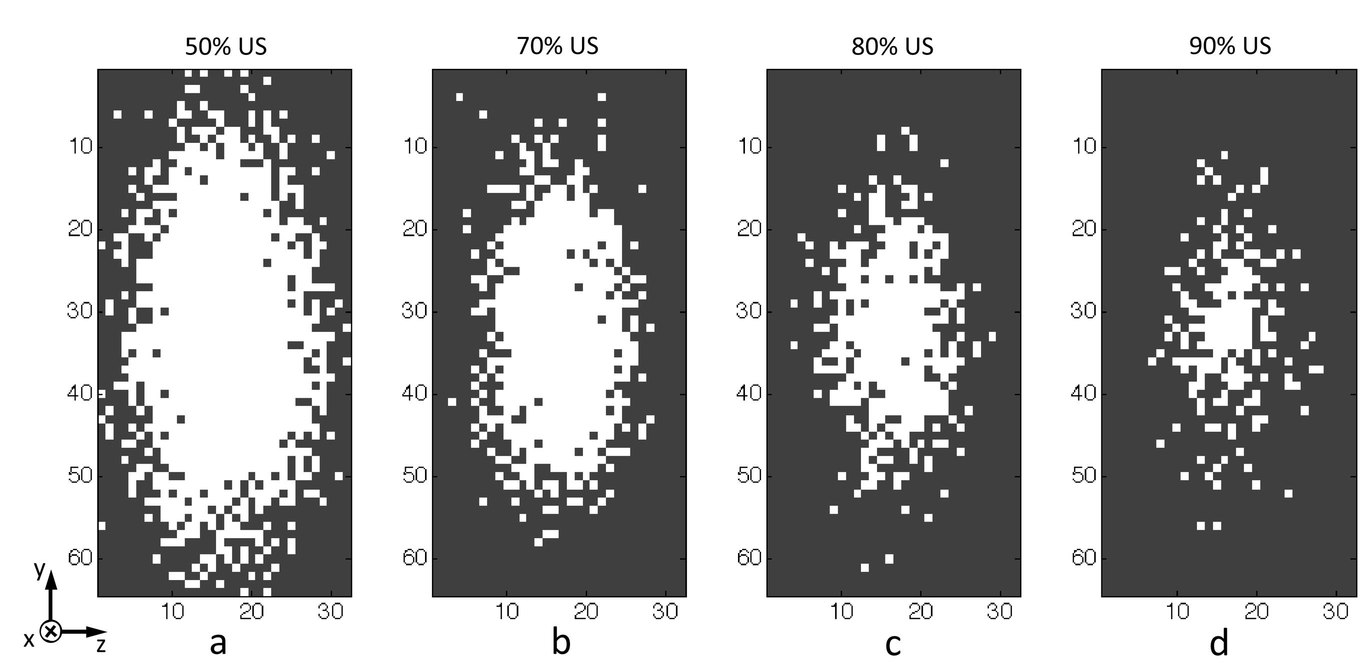
Balanced steady state free precession (b-SSFP) imaging sequences are fast and efficient. However, b-SSFP requires a stable and homogenous field to avoid imaging artifacts. Permanent and electromagnets typically do not have the stability for b-SSFP. Our 6.5 mT, bi-planar electromagnet shown above has > 20 ppm stability (6 Hz) over a 20 cm sample, allowing us to implement b-SSFP. Also shown are the 10 cm NMR solenoid coil and the 7 cm Aldermann-Grant EPR coil.

To the right is a simulation of the sensitivity of b-SSFP to off resonance effects using our sequence parameters. The transverse magnetization is constant for only ± 5 Hz from resonance. Inputs are α = 90°, T1/T2 = 540/490 ms, and TR/TE = 54/27 ms.

Off Resonance Effects



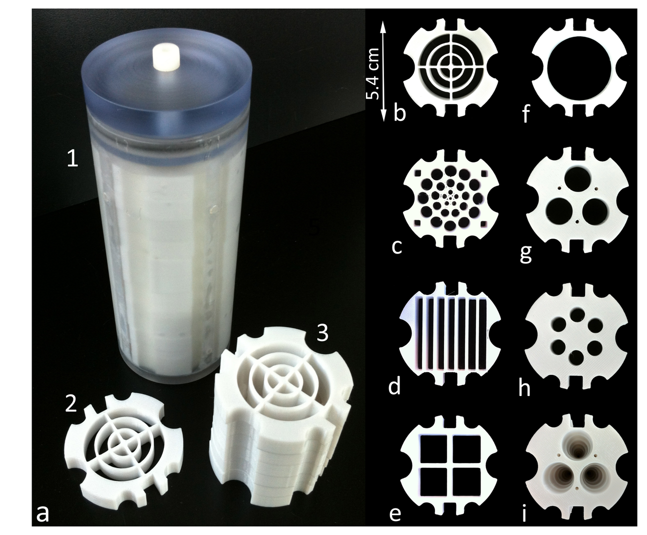
Undersampling and Compressed Sensing

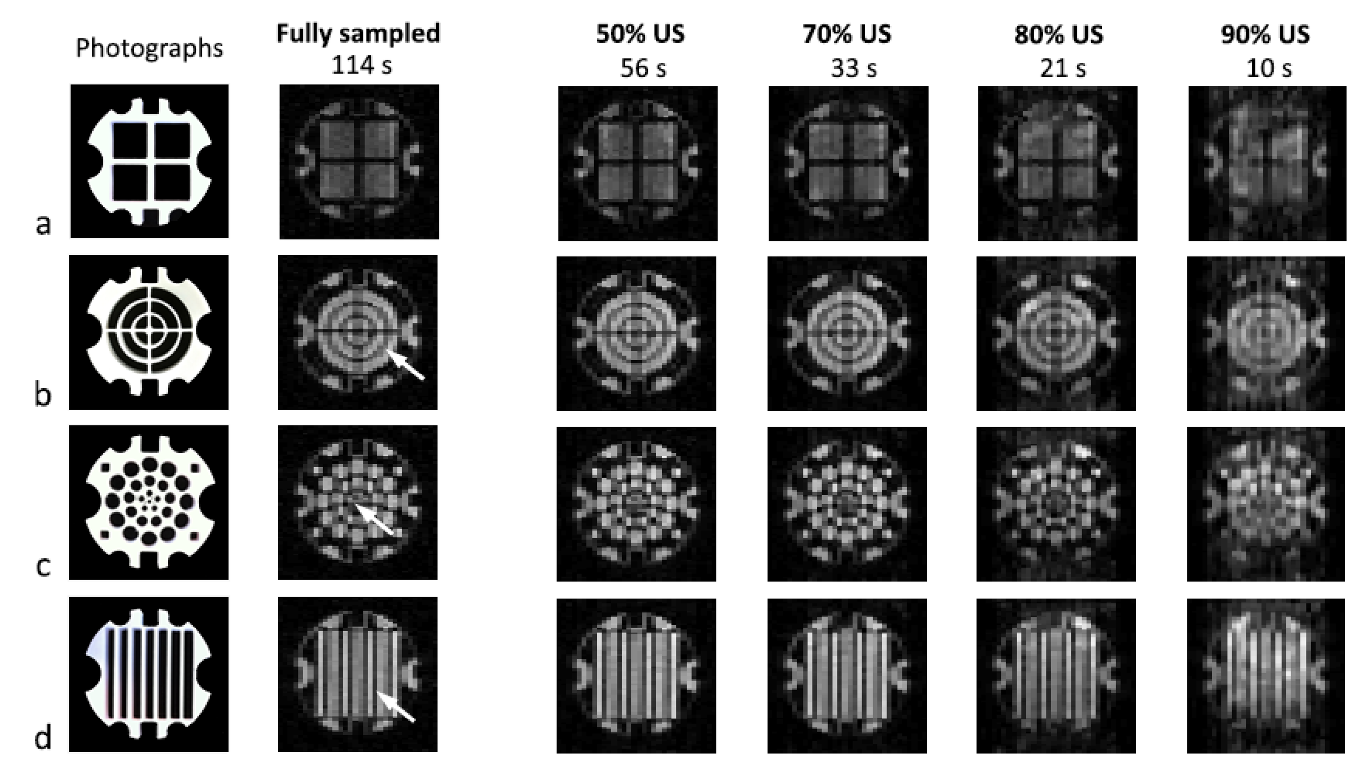


Most images can be represented by a small number of coefficients when transformed into the proper basis, here the Dirichlet wavelet transform is used. We exploit this to reduce the k-space data acquired. Random lines of k-space in the phase encode directions were chosen from a Gaussian distribution to emphasize the center of k-space while still obtaining high frequency content and producing incoherent artifacts. Compressed sensing is a framework exploiting sparsity to reconstruct MR images from undersampled k-space data [3]. Free MATLAB code, Wavelab 850 was used to reconstruct undersampled images.

Overhauser b-SSFP Images

The ability of compressed sensing to accurately reconstruct undersampled data depends on the undersampling mask and the details of the object being imaged. We designed and 3D printed a phantom to contain many different features and sizes to evaluate the robustness of compressed sensing reconstruction and the ability to resolve small spatial features.

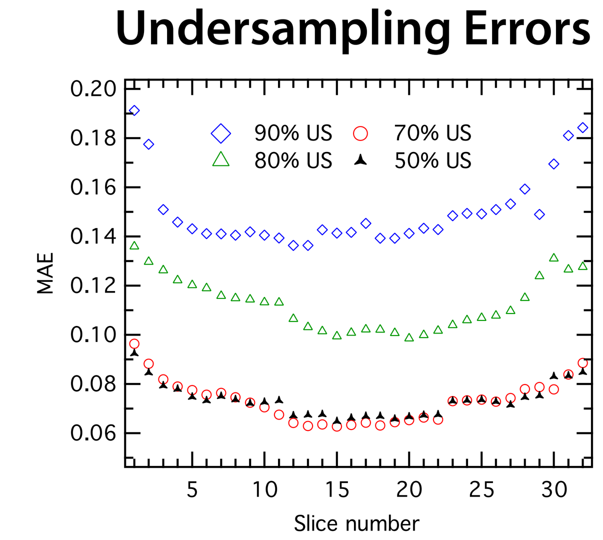




Four representative slices from a 32 slice data set. 50% and 70% undersampling rates accurately reproduce the object. ***All images are NA = 1 at 6.5 mT!*** Sample was 2.5 mM TEMPO in water. Signal intensity is ~ 30X larger using DNP than thermal polarization. With 70% undersampling, a full 3D, 128x64x32 matrix, was acquired in 33 s with 2x1x3.5 mm resolution. TR/TE = 54/27 ms.

Using the fully sampled data set as a reference, the mean absolute error (MAE) was calculated for each undersampling rate and is shown to the right. The differences between the fully and undersampled data for 50% and 70% are small and nearly equal implying little loss in information from 70% undersampling. At 80% and 90% the errors become more severe. The increased error at the edges comes from the B_1 profile of the Aldermann-Grant coil.

Undersampling Errors



Conclusion

The combination of applying EPR saturation during the phase encode gradient step along undersampling results in 7 fold increase in temporal resolution compared to other published results [4]. While b-SSFP may not be possible for other OMRI setups due to the demands of field homogeneity, undersampling and embedded EPR saturation should easily transfer to other OMRI imaging sequences.

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References - [1] Sarracanie, *et al. Magn. Reson. Med.* doi: 10.1002/mrm
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