Spectrally Resolved Fully Phase-Encoded 3D Fast Spin-Echo for Metal Artifact Reduction and Spectroscopic Imaging

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Introduction When voxels contain a wide distribution of off-resonance spins, the use of frequency encoding in MRI is limited because it leads to spatial distortion artifacts. Recent work, such as SEMAC[1] and MAVRIC[2], have dramatically reduced artifacts associated with imaging near metal, but both methods use frequency encoding and are limited in their ability to minimize distortion artifacts in that direction. The purpose of this work was to develop a spectrally-resolved, fully phase-encoded 3D fast spin-echo technique, unique from other other single point techniques[3]. This technique eliminates all frequency-encoding-related shift artifacts and permits spectral sampling at each spin-echo, allowing highly accurate imaging of off-resonance spins and enabling spectroscopic imaging with much higher spatial resolution than current methods.

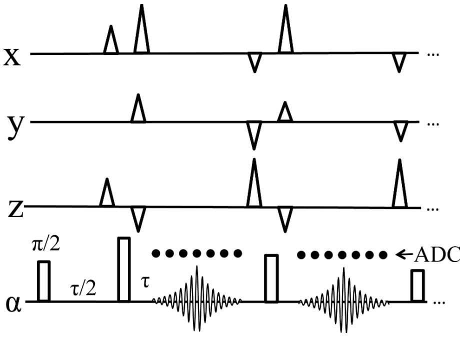

Figure 1: Proposed pulse sequence with phase encoding in all three dimensions, temporal sampling of each spin-echo, and no frequency encoding gradient, entirely avoiding distortion from off-resonance effects. A variable flip angle schedule for the refocusing pulses, motivated by CUBE[4], permits an extended echo train needed for the 3D-FSE acquisition.

Methods A new pulse sequence was developed with phase encoding in all three dimensions and no frequency encoding (readout) gradient, using a 3D fast spin-echo excitation scheme with extended refocusing trains using modulated flip angles[4] (**Fig 1**). Each spin-echo was sampled temporally to provide spectral decomposition and high SNR performance. For feasibility testing, a ping-pong ball filled with a 0.065 mM solution of gadobenate dimeglumine was suspended by a thread in a water phantom and imaged with a single channel T/R head coil at 1.5T. Acquisition parameters included: FOV = 17.4x17.4x17.4cm^3, matrix = 124x124x124, TR = 2.2s, ETL= 124, BW = ±7.81 kHz, with scan time of 9 hr, 24 min. Across each spin-echo, 128 independent samples were collected over an 8ms period yielding a spectral resolution of 122Hz. Spectroscopic images were obtained through Fourier transform in time on a voxel-by-voxel basis. Selected spectral bins were color coded in 3D and combined using Mimics (Materialise, Leuven, Belgium). For comparison, a fully-sampled conventional 3D-FSE was performed with the same imaging parameters but with a 4.5 min scan time.

The 128 time point signal can be modeled for multiple or single species as

Eqn 1 $$S_n(\boldsymbol{r}) = \left(\sum_{m=1}^{M} \rho_m(\boldsymbol{r}) e^{i2\pi\Delta f_m(\boldsymbol{r})t_n}\, e^{-R^*_{2m}(\boldsymbol{r})\,|t_n|}\right) e^{i2\pi\Psi(\boldsymbol{r})t_n}$$

Eqn 2 $$S_n(\boldsymbol{r}) = \rho_m(\boldsymbol{r}) e^{-R^*_{2m}(\boldsymbol{r})\,|t_n|} e^{i2\pi\Psi(\boldsymbol{r})t_n}$$

where $S_n(\mathbf{r})$ = measured signal for voxel r, t_n = time at sample n relative to spin-echo, ρ = proton density, Δf = frequency offset from water, and $\Psi = B_0$. Using a non-linear least squares curve fitting algorithm (lsqnonlin in Matlab) on a voxel by voxel basis, ρ(r), Ψ(r), and R_2*(r) were estimated.

Images of a titanium hip prosthesis were also acquired with the new sequence using 80μs hard RF pulses and the following parameters: FOV = 23.0x11.5x6.4cm^3, matrix = 100x50x28, TR=2.3s, ETL=100, BW=±7.81 kHz, with a scan time 53min, 41s. Using similar scan parameters, a 128x64x28 conventional 3D-FSE was also acquired using standard RF pulses and BW = ±20.8 kHz. Preliminary acceleration results, to be described fully in a separate work, are also displayed after retrospectively undersampling the data using a Poisson disk pattern and reconstructing with SPIRiT[4].

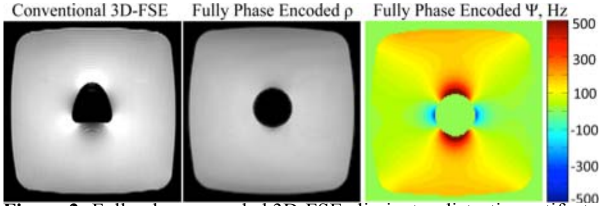
Conventional 3D-FSE
Fully Phase Encoded ρ
Fully Phase Encoded Ψ, Hz

Figure 2: Fully phase encoded 3D-FSE eliminates distortion artifact and also provides a field map of the Bo inhomogeneity

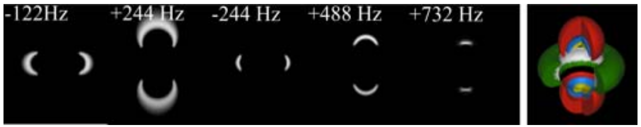

Figure 3: Spectroscopic images at distinct frequency bins (Hz) that have been color coded in 3D and summed together on the right.

Results Figure 2 compares conventional 3D-FSE, which shows severe distortion, unlike the ρ(r) and Ψ(r) images estimated using the signal model above (**Fig 2**). Ψ(r) maps clearly show dipole effects from the sphere that agree closely with selected spectral bins shown in **Fig 3. Fig. 4** images of the titanium hip prosthesis with minimal artifact using the proposed method, unlike the conventional 3D-FSE image that suffers from distortion (**Fig 4**). The prosthesis is clearly depicted in the SPIRiT image, using an R=5.4.

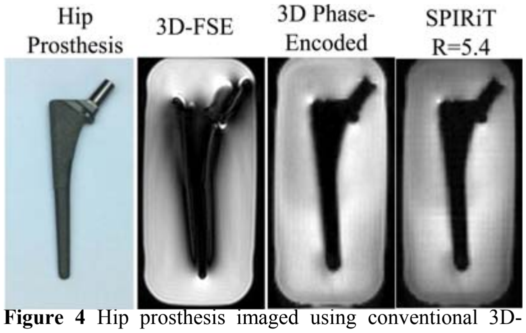
Hip Prosthesis
3D-FSE
3D Phase-Encoded
SPIRiT R=5.4

Figure 4 Hip prosthesis imaged using conventional 3D-FSE, and the proposed method. Preliminary results using SPIRiT after artificial undersampling (R=5.4) is shown.

Discussion To our knowledge, this is the first fully phase encoded technique to utilize a 3D-FSE acquisition and the first to incorporate spectral encoding. Preliminary data demonstrates great potential for both metal artifact reduction and high spatial resolution spectroscopic imaging. The largest remaining challenge is the scan time. Our preliminary results with SPIRiT are promising and will be detailed in future work. An inherent advantage of this spectrally resolved 3D phase encoded technique is that all k-space samples are fully independent which may prove useful for improving and optimizing acceleration methods. The method is compatible with many acceleration options including parallel imaging, compressed sensing, partial Fourier, corner cutting and variable density sampling. In addition, the spectroscopic acquisition yields very high SNR with effective averaging of ~128, facilitating high acceleration factors. We anticipate such methods will successfully accelerate acquisitions to within clinically acceptable scan times.

References [1]Lu et al. MRM 2009;62:66-76. [2]Koch et al. MRM 2009;61:381-390. [3]Balcom et al. JMRI 1996;123:53–61. [4]Busse et al. MRM 2006;55:1030-1037. [5]Lustig et al. MRM 2010;64:457–471.

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