Dual-band RF Shimming at High-Field with Parallel Excitation

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Introduction: High-field imaging offers significant potential benefits, such as improved SNR, contrast, and spectral dispersion. However, there are some well-recognized issues for imaging at high field, including reduced RF homogeneity. One approach for obtaining homogenous slice excitation is to use a 3D selective excitation [1]. This has also been combined with transmit SENSE to improve performance [2-3]. We identify a significant problem with these current design approaches in their ability to adequately shim simultaneously over multiple resonances (e.g. water and fat), and then go on to describe a solution that is validated on a parallel-transmit body array.

Methods: A time-optimized 3D spokes trajectory was designed to cover a k-space trajectory as shown in Fig. 1. This included a central DC spoke sufficient for exciting a 1-cm thick slice using an RF pulse with time-bandwidth of 4, as well as 6 spokes spaced circumferentially at a radius corresponding to 1/FOV that covered a k_z range 70% that of the DC spoke as in [2].

The RF pulse design was broken into separable problems of (a) designing a conventional slice-selective excitation and (b) designing the complex weighting for each spoke RF subpulse to account for the in-plane B_1 inhomogeneity in x,y as in [2-3]. Part (a) was simply solved by using an SLR-designed pulse. For part (b), we adopted the image-domain approach for formulating the parallel transmit design [4]. The in-plane magnetization profile can be described in matrix form as $\mathbf{m} = A\mathbf{b}$, where $\mathbf{m}$ is the desired magnetization vector, and $\mathbf{b}$ is an Nspoke x Ncoil length vector of the complex weighting applied to each spoke subpulse. The matrix A includes the effects of the B_1 sensitivity profile, k-space trajectory and in-plane off-resonance as in [5]. As described in [6], it is preferable to remove any phase constraint on $\mathbf{m}$ when possible, so rather than use a linear solution to this problem as in [2-3, 5], we used a nonlinear optimization (fminunc, Matlab, The MathWorks) to solve for $\mathbf{b}$ that minimizes $(\| |A\mathbf{b}| - \mathbf{m} \|^2 + \lambda \|\mathbf{b}\|^2)$ subject to $|b_i| < RF_{max}$, where RF_{max} is the peak RF amplifier output, and λ is a regularization factor.

While this formulation does account for B_0 variations in-plane, it does not account for a heterogeneous mixture of resonant frequencies such as water and fat. However, a dual-band design can be obtained by augmenting the matrix A to account for two sources of B_0 variation—one from main field homogeneity $B_0(x,y)$ and another from chemical shift $B_{CS}(x,y) = F_{CS} + B_0(x,y)$, where F_{CS} is the chemical shift. This dual-band design was further improved by trying a limited set (~30-50) of random permutations of the order in which the spokes are traversed.

Results: B_0 and B_1 maps of a salted water phantom inside a 3T TEM body array with 8 effective elements (cross-diameter elements of a 16-element array were driven in tandem but with opposite phase) on an 8-channel parallel transmit GE Signa HD system (23 mT/m, 77 T/m/s) were acquired using a multi-tip excitation approach similar to [7]. The results of a conventional 3D spokes excitation design (5-ms duration) are shown in Fig. 2a-b. While receive sensitivity shading is still present, it is clear that the RF shim over the fat resonance is markedly degraded. In contrast, the dual-band results shown in Fig. 2c-d show consistent shimming performance at both water and fat resonances. The relative RMS error of the simulated shim went from 3% for the water-only shim to 8% for the dual-band shim. The relative RMS error of a simulated shim using only the DC spoke was 14% for comparison.

Figure 3 illustrates the B_1 map for a single effective element of the TEM body array as measured on a large sample of *ex vivo* meat, as well as the response of a dual-band (water/fat) 3D spokes excitation.

Discussion: It has been demonstrated that a conventional 3D spokes excitation design is inappropriate for simultaneous shimming over multiple resonances such as water and fat. A new dual-band approach is presented that resolves this issue at the cost of degrading the shim performance on a single resonance. For greater spectral dispersion, static RF shimming may be an attractive alternative.

References: [1] Saekho et al., MRM, 55:719-724, 2006. [2] Setsompop et al., MRM, 56:1163-71, 2006. [3] Zhang et al., MRM, 57:842-847, 2007. [4] Grissom et al., MRM, 56(3):620-29, 2006. [5] Setsompop et al., Proc. ISMRM 15, p. 671, 2007. [6] Kerr et al., Proc. ISMRM 15, p. 1694, 2007. [7] Vogel et al., Proc. ISMRM 15, p. 1658, 2007.
[Acknowledgement: This work partly supported by NIH R01 EB005307, NIH R01 EB008108, and NIH R21 EB 007715.]

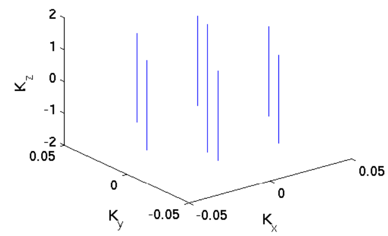

Figure 1: 3D k-space paths (cycles/cm) used for selective excitation of a 40-cm FOV. Transition gradients between k_z spokes are not shown.

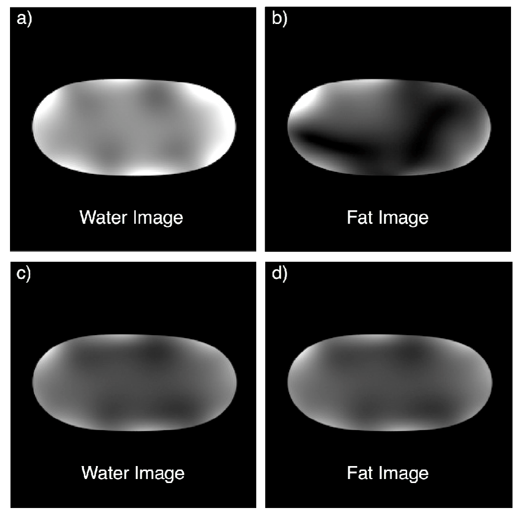

Figure 2: Images acquired at 3T using conventional 3D spokes excitation of a salted water phantom (a) on resonance and (b) with the center frequency shifted +460Hz so that the phantom mimics a fat resonance. Note the significant degradation in the RF shimming performance. In contrast, (c) and (d) show the consistent RF shimming performance offered by the dual-band design. Receive-sensitivity shading is still present in all images.

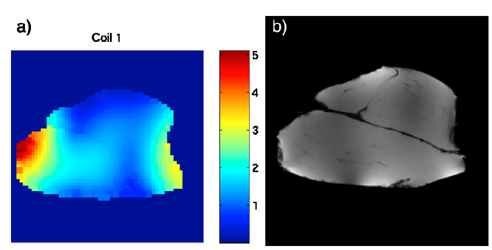

Figure 3: a) B_1 map in uT of single channel (two cross-diameter elements of 16-element TEM body array driven with opposite phase) on large meat sample. b) Dual-band (fat/water) 3D spokes excitation result showing uniform excitation, though with receive-sensitivity shading still present.