Accelerated Water-fat Separation Using Parallel Imaging, Compressed Sensing, and Multiscale Cubic B-splines

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INTRODUCTION: Chemical shift-encoded water-fat separation techniques are used in both research and clinical settings because they are highly robust to off-resonance. A tradeoff when using these techniques is a longer scan time since data must be collected at multiple echo-times. Previous works have proposed to use either parallel imaging (PI) [1] or compressed sensing (CS) [2,3] to shorten the scan time. In this work, we introduce a joint parallel imaging and compressed sensing approach for water-fat separation. The proposed approach is compared to an existing PI/water-fat separation [4-6] method. We show 3.4x 1D acceleration with the proposed approach, while the existing method is limited to 1.9x 1D acceleration.

THEORY: We model the noisy undersampled k-space measurements (k) as a function of the unknown coil sensitivities (C), unknown coil-independent water and fat images (ρ), unknown B0 field map (Ψ), known k-space sampling (F_u), and known chemical-shift modeling (A) (Eq. 1). The coil maps are derived from the SPIRiT [7] k-space kernel [8,9]. The water and fat images are estimated by Eq. 2 where λ is the regularization parameter and W is the Daubechies-4 wavelet transform. The B0 field map is updated by Eq. 3 where $\Delta\psi$ is the field map update term, $\Delta\rho$ is the water-fat error term, r is the residual, x is the linear function relating $\Delta\psi$, $\Delta\rho$ to r, and B_m is the cubic B-splines (CBS) basis at the m^{th} scale (Fig. 1). The reconstruction procedure is summarized below:

1) derive coil sensitivities from 16 central k-space lines
2) initialize B0 field map to zero and choose the coarsest-scale B-splines ($m = 1$)
3) estimate the water and fat images (Eq. 2)
4) update field map estimate using B-splines at the m^{th} scale (Eq. 3)
5) IF max $|\Delta\psi|$ < 1Hz THEN go to step 6 ELSE go to step 3
6) IF $m = m_{max}$ THEN done ELSE $m = m + 1$, go to step 3 (m_{max} defines finest-scale CBS basis)

METHODS: Fully-sampled axial liver data were collected at three echo-times (TE_1 = 2.184ms, ΔTE = 0.794ms) on a GE Signa EXCITE HDx 3T system (GE Healthcare, Waukesha, WI) using an investigational 3D IDEAL SPGR sequence and eight-channel torso array. The acquisition matrix size was 256x256 with 8 slices. The fully-sampled data were undersampled by net factor of 3.4x using a jittered grid pattern [10] and reconstructed using the proposed PI-CS-CBS method. For reference, the fully-sampled data were reconstructed using IDEAL with region-growing (IDEAL-RG) [5,6]. For comparison, the data were uniformly undersampled by net factor of 1.9x (= 2x + 16 central k-space lines) and 3.4x (= 4x + 16 central k-space lines) and were reconstructed using ARC [4] and then IDEAL-RG (ARC/IDEAL-RG).

RESULTS: Fig. 2 shows the estimates from the reference 1x IDEAL-RG, 3.4x ARC/IDEAL-RG, and 3.4x PI-CS-CBS. The 1.9x ARC/IDEAL-RG estimates were similar to the reference (not shown). The 3.4x proposed PI-CS-CBS method yields similar estimates as the reference whereas the 3.4x ARC/IDEAL-RG estimates exhibit unresolved aliasing and noise amplification.

CONCLUSION: We have demonstrated uniform water-fat separation using a joint PI-CS approach. The proposed approach achieves 3.4x 1D undersampling, which outperforms ARC/IDEAL-RG and more than makes up for the additional scan time of a three-point acquisition.

REFERENCES: [1] Ma et al. ISMRM 2003 p.1069 [2] Doneva et al. MRM 2010;64:1749-59 [3] Sharma et al. MRM (early view) [4] Beatty et al. ISMRM 2007 p. 1749 [5] Reeder et al. MRM 2005;54:636-44. [6] Yu et al. MRM 2005;54:1032-39 [7] Lustig et al. MRM 2010;64:457-71 [8] Lustig et al. ISMRM 2011 p. 479 [9] Lai et al. ISMRM 2011 p.65 [10] Cook. ACM Trans Graph 1986;5:51-72

(1) $k = F_u C \Psi A \rho + N(0,\sigma^2)$

(2) $\min_{\rho} ||k - F_u C \Psi A \rho||_2 + \lambda |W\rho|_1$

(3) $\min_{\Delta\psi,\Delta\rho} ||r - x(\Delta\psi,\Delta\rho)||_2 + \lambda |W\Delta\rho|_1$ s.t. $\Delta\psi \in \text{span}\{B_m\}$

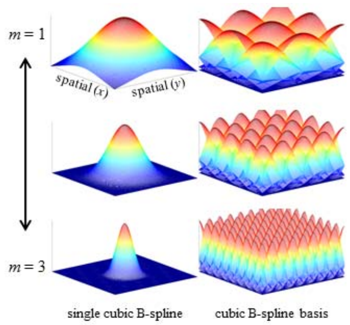

Fig. 1: cubic B-spline (left) and corresponding basis (right); field map update at the m^{th} scale is restricted to be in the space that is spanned by the m^{th} cubic B-spline basis

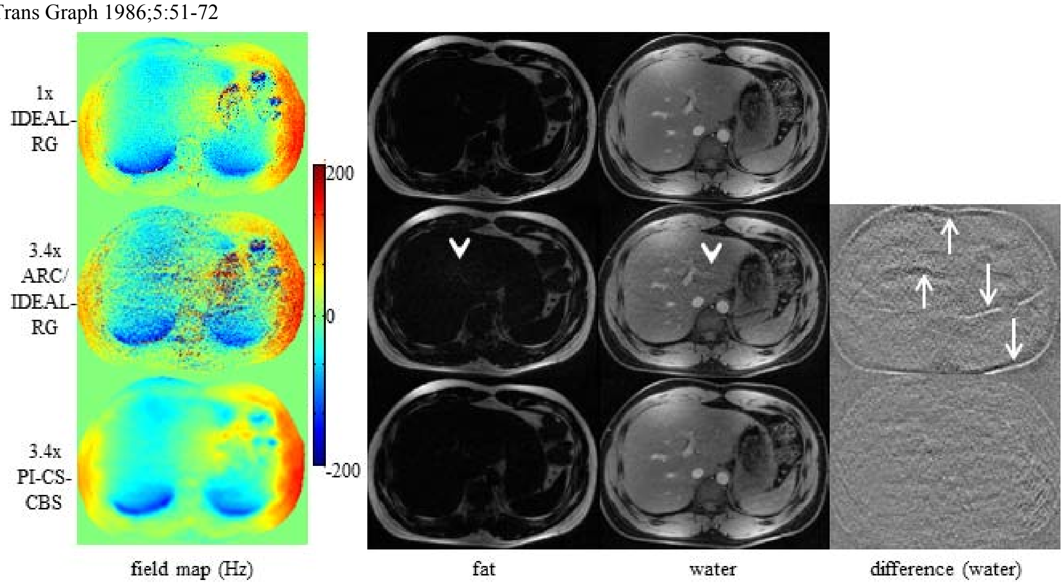

Fig. 2: water, fat, and B0 field map estimates using the three reconstruction methods; the difference images are shown on the same window/level, using 1x IDEAL-RG as the reference; the ARC/IDEAL-RG estimates exhibit unresolved aliasing (arrows) and noise amplification (arrowheads) that do not appear in the proposed PI-CS-CBS reconstruction