Water-Fat Separation with IDEAL-SPGR

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Introduction: Uniform fat suppression is necessary for many MR imaging applications and can be challenging in the presence of B_o and B_1 field inhomogeneities. The use of gradient echo acquisitions in combination with "Dixon" methods can be used to achieve uniform water-fat separation insensitive to B_o field inhomogeneities [1]. Typically, three echoes, shifted with respect to TE=0, are acquired to create time dependent phase shifts caused by water-fat chemical shift differences. Noise analysis of fast spin-echo (FSE) imaging and IDEAL (Iterative Dixon water-fat separation with Echo Asymmetry and Least-squares estimation) water-fat separation has shown a strong SNR-dependence on the relative proportion of water and fat within a voxel, as well as the absolute position of acquired echoes [2-6]. Theoretical predictions from this work show that the optimal echo combination for IDEAL-FSE occurs when the phase of the three echoes is separated by 2π/3, and the middle echo is centered at π/2, ie: (-π/6, π/2, 7π/6). With these echo times the SNR performance of IDEAL-FSE reaches its maximum possible for all proportions of water and fat. The purpose of this work is to extend and experimentally verify this optimization for spoiled gradient echo imaging (IDEAL-SPGR).

Theory: Recent theoretical work demonstrates that for three-point acquisitions, the optimal echo combination has the transverse magnetization of water perpendicular to that of fat at the acquisition of the middle echo and the other two echoes are acquired 2π/3 earlier and later, respectively, ie: (-π/6+πk, π/2+πk, 7π/6+πk), where *k*=any integer [4,5]. For SPGR imaging, *k* must be chosen such that TE>0. For example, for *k*=1 and *k*=2, the corresponding echo times at 1.5T are (1.98, 3.57, 5.16ms) and (4.36, 5.95, 7.54ms), respectively. Deviation from these echo combinations will result in less than optimal SNR performance of the water-fat decomposition.

The noise performance of a water-fat decomposition is conveniently described with the effective number of signal averages, or *NSA*, defined as:

$$NSA = \sigma^2 / \sigma_\rho^2 \qquad (1)$$

where σ^2 is the variance of the noise in a source image and σ_ρ^2 is the variance of the noise in a calculated water or fat image. For any three-point Dixon water-fat decomposition method, the maximum possible NSA is three, which is equivalent to what would be obtained if the object contained only water or only fat, and the three source images were averaged. For example, with *k*=1 (5π/6, 3π/2, 13π/6), theory predicts NSA=3 for all proportions of water and fat. If water and fat are aligned at the center echo, eg. (4π/3, 2π, 8π/3), NSA is severely degraded for voxels with mixtures of water and fat [2-5].

Methods: Phantom experiments were performed to quantitatively validate the theoretically expected noise behavior of the water-fat decomposition. A spherical phantom consisting of peanut oil floating on 0.9% normal saline doped with 5mM $NiCl_2$ was imaged at 1.5T (GE TwinSpeed, Milwaukee, WI) with a 2D-SPGR pulse sequence modified to shift the readout gradient. An obliquely oriented slice was prescribed through the oil-water interface in order to create a continuum of fat:water ratios across the resulting image. An extremity coil (Medical Advances) and the following image parameters were used: N_x=256 , N_y=256 , 1 excitation, FOV=24cm, slice=10mm, BW=±83.3kHz, TR =10.0ms, flip=20°. Product automated shim routines were used. The flip angle was chosen empirically to produce similar signal intensity from water and fat. Acquisition was performed with IDEAL echoes (5π/6, 3π/2, 13π/6): echo times=1.98, 3.57, 5.16ms at 1.5T, and for the "aligned" echo combination (4π/3, 2π, 8π/3): echo times=3.18, 4.76, 6.35ms. For each echo combination, the acquisition was repeated 256 times (scan time=32:45min). Water and fat images were reconstructed with an on-line iterative least-squares algorithm [2], using a "robust" algorithm that prevents water-fat ambiguities [7]. NSA was calculated on an individual pixel basis using Eq. 1, and pixels outside the phantom were excluded using a threshold mask. For each pixel, the fat:water ratio was calculated from the average of all water and the average of all fat images, and scatter plots of measured NSA vs. fat:water ratio were made.

All human scanning was performed at 1.5T (Signa TwinSpeed, GE Healthcare, Milwaukee, WI). Imaging in the knee of one normal volunteer and in the abdomen of a second volunteer was performed with IRB approval and informed consent. We used a modified 3D-SPGR pulse sequence to acquire three images with different echo shifts. Imaging of the knee was performed with a quadrature extremity coil (Medical Advances), with the following parameters: N_x=512, N_y=416, N_z=48, FOV=16cm, slice=2mm, BW=±62.5kHz, TR=12.4ms, TE=(4.36, 5.95, 7.54ms), flip=9°, for a scan time of 9:50. 3D breath-hold imaging of the abdomen was performed with IDEAL-SPGR using an 8-element phased array coil, and the following imaging parameters: TR=8.0ms, TE=(1.98,3.57,5.16ms), N_x=256, N_y=160, N_z=45, FOV=36x24cm, BW=±32kHz, flip=20°, with complete liver coverage in a 24sec breath-hold using a parallel imaging acceleration of 2.

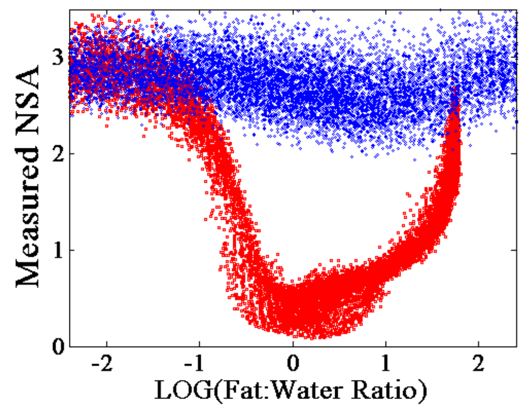

Figure 1: Experimental NSA for different fat:water ratios measured from a slice obliquely oriented through oil-water interface of the phantom. Results from IDEAL echoes (5π/6, 3π/2, 13π/6) are shown in blue and "aligned" echoes (4π/3, 2π, 8π/3) are shown in red.

Figure 2: Calculated water images from 2 slices of a 3D-IDEAL-SPGR acquisition in the knee. Voxel size: 0.35x0.38x2mm

Results: Figure 1 plots the NSA of the IDEAL echo combination (5π/6, 3π/2, 13π/6) and "aligned" echo combination (4π/3, 2π, 8π/3). Experimental measurements indicate uniform noise performance of IDEAL near the maximum of 3 for all fat:water ratios. Although NSA is 3 for both cases for pixels containing mostly water, significant degradation of noise performance is seen for the "aligned" approach, indicating the inability to resolve water and fat when water and fat are in similar proportions. Figure 2 shows calculated water images from two slices of a 3D-IDEAL-SPGR acquisition in a knee, and figure 3 shows dynamic contrast-enhanced 3D-IDEAL-SPGR images of the liver acquired in the arterial phase.

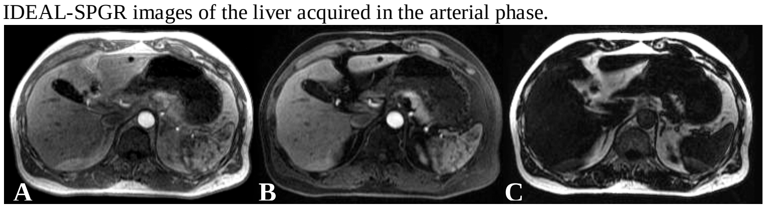

Figure 3: 3D-IDEAL-SPGR images of the liver during the dynamic contrast enhancement a) recombined, b) water, c) fat images

Discussion: Experimental measurements of NSA confirm theoretical predictions and indicate that the optimum SNR occurs when echoes are shifted such that the phase shift between water and fat is (-π/6+πk, π/2+πk, 7π/6+πk), where *k*=any integer. Using these parameters, high quality, high SNR IDEAL-SPGR images with uniform water-fat separation can be obtained for a variety of applications in the body.

References: **1.** Wang et al, JRMI., 1998: 8:703-10 **2.** Reeder et al, MRM, 2004, 51:35-45. **3.** Wen et al ISMRM 2003, p483 **4.** Pineda et al, ISMRM 2004, p2107 **5.** Pineda et al, submitted to MRM, 2004. **6.** Reeder et al**,** ISMRM 2004, p 696 **7.** Yu et al, ISMRM, 2004, p345.