Chemical Shift Based Water-Fat Separation With An Undersampled Acquisition

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INTRODUCTION: Previous high resolution 3D balanced steady state free precession (bSSFP) imaging methods with fat/water separation generally assume well-behaved B0 environments [1]. The IDEAL [2] chemical shift based water-fat separation method provides a means to handle more demanding B0 environments, but its need for redundant sampling limits the resolution achievable in a set scan time. In this work we present a method termed IDEAL 3DPR-SSFP in which individual echo time images for IDEAL utilize uniquely sampled k-space data with a 3D radial out and back trajectory. Even and odd echo times are sampled in separate TRs to better accommodate the timing constraints of bSSFP. The method is demonstrated in the breast and knee.

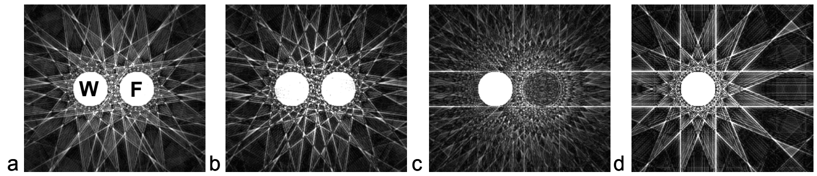

Figure 1. Digital simulation of water (W) and fat (F) objects sampled with unique radial data at each echo time t_1 (a) to t_n (b) so undersampling artifacts vary spatially at each echo time. All images are windowed to demonstrate artifact. Sampling unique radial lines at each echo time reduces streak artifact in the IDEAL water image (c) as combining water signal from all echo times eliminates nearly all water-based artifacts. However, undersampled artifacts from fat are not completely resolved and some fat artifacts are evident in the water images. Conversely, if the same set of radial lines is sampled at each echo time, fat artifacts are resolved through IDEAL processing, however streak artifacts reflect the higher degree of water undersampling present at each echo time (d).

THEORY AND METHODS:

In this method, the ensemble of all radial lines is comprised of a set of N echo times, but each individual echo time is undersampled by a factor N. A B0 map can be generated from the adequately sampled center of k-space within each echo, accurate to N pixels. This is not a limitation, as in IDEAL the B0 map is generated at a lower resolution than the output image data. The iterative IDEAL algorithm effectively corrects each source image before decomposing the signal into fat and water channels. In the water channel, the IDEAL decomposition sums water signal from each of the B0-corrected source images. As combining the water signal is linear, undersampling artifacts from water in each of the source images destructively interfere in the IDEAL calculated water image. Undersampling artifacts from fat in each of the individual echo time images should only partially interfere in the IDEAL calculated water image, as there is a phase shift in the fat signal due to the different acquisition times.

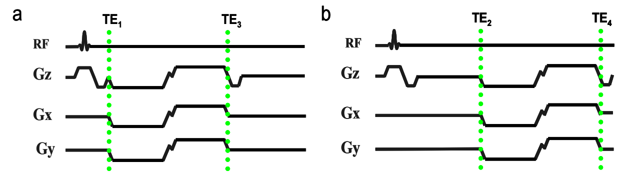

Figure 2. Acquiring the first and third echo time within one TR (a) and the second and fourth echo time within a second TR (b) allows for the acquisition of high resolution data with a radial trajectory while still meeting the requirements of IDEAL echo spacing and a short TR to best mitigate the characteristic banding artifacts of bSSFP.

To asses the effect of sampling a unique set of radial lines at each echo time, a 2D digital phantom of a water and fat object was sampled with 3 interleaved sets of radial k-space lines for echo times of $-\pi/6$, $\pi/2$, $7\pi/6$ [3] (Figure 1a-b). A high degree of undersampling was used to emphasize manifestation of undersampling artifacts. Images were processed with IDEAL in Matlab. Resultant IDEAL water images were compared to IDEAL water image when each echo time is sampled with the same set of radial lines.

The IDEAL 3DPR-SSFP pulse sequence incorporates two 3D radial passes of data with two radial lines acquired per TR (Figure 2). While the echo spacing with this trajectory necessarily varies somewhat with spatial resolution, robust fat/water separation in IDEAL is much less dependent on the exact choice of echo spacing when more than 3 echoes are collected [3]. Acquiring odd and even echo times in separate TRs facilitates the acquisition of high resolution data within the timing constraints of IDEAL and bSSFP. A TR of 4.5 ms was selected so that water and fat are each centrally located in a passband in the bSSFP response spectrum and spatial encoding time within each TR is doubled in comparison to the consecutive acquisition of the echoes. Echo times of 0.3,1.5,2.9,4.0 ms were selected at 1.5T to produce 0.6 mm isotropic resolution in a 5 minute scan.

RESULTS AND DISCUSSION:

Results of digital phantom simulation indicate that sampling a unique set of undersampled radial lines at each echo time significantly reduces the water undersampling artifact in IDEAL (Figure 1c) in comparison to the artifact that would occur if the same undersampled set of radial lines were sampled at each echo time (Figure 1d). While the artifact from water is reduced, some undersampling artifact from the fat signal remains in the water channel (Figure 1c). However, the level of remaining fat artifact in the water channel is less than the level of water artifact that would remain if the same set of radial lines were sampled at each echo time.

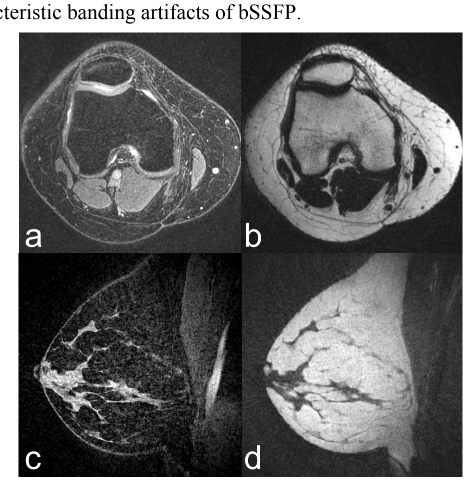

Figure 3. Water (a,c) and fat (b,d) IDEAL 3DPR-SSFP images acquired in the knee (a,b) and breast (c,d). Isotropic 0.63 mm resolution is achieved with a 20 cm FOV in a total scan time of 5 minutes. Effective fat-water separation and depiction of fine structures is achieved in a clinically feasible scan time of 5 minutes.

IDEAL 3DPR-SSFP achieves high isotropic resolution with bSSFP contrast and effectively separates water and fat in vivo in the knee and breast (Figure 3). Fine structure detail is evident in these asymptomatic volunteers and opportunity exists to further improve resolution through implementation of the technique at 3 T. Overall image quality is better in the knee than in the breast, possibly owing to streaks emanating from tissue outside the field of view due to the sagittal excitation used in the breast. Also of note is the resolution in five volunteer breast datasets of fat-water swaps which commonly occur in the superior region of the breast near the chest wall.

CONCLUSIONS: IDEAL 3DPR-SSFP provides superior separation of fat and water in high resolution bSSFP datasets. Fat-water separation is effective despite sampling a unique set of radial lines at each echo time. Though artifact from water only reflects the degree of undersampling remaining after combining all echo times, some undersampling artifact from fat remains in the water images. Future work will include investigating removal of the fat artifact in the water images, as the availability of a fat image may provide information to estimate the undersampling artifacts from the fat so they can be eliminated from the water image volume.

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References 1. Moran C, et al., *JMRI*, 30:135-44, 2009. 2. Reeder S, et al., *MRM*, 54:636-44, 2005. 3. Pineda A, et al., MRM, 54:625:35, 2005.