3D balanced SSFP Dixon imaging with Band-Reduction at 3T

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Introduction: Balanced steady-state free precession (bSSFP) imaging provides rapid, high-SNR, 3D T_2-like contrast images [1,2], and has been shown to work with Dixon-based fat/water separation schemes [3-7]; however, it suffers from bands of signal variation due to field inhomogeneity. This work explores the adverse effect that the multiple fat peaks can have on Dixon separation, because the bSSFP profile of fat can vary with echo and repetition time. We propose a method that removes banding artifacts in both the separated fat and water signals, allowing bSSFP to be used at higher field strengths where banding artifacts are more pronounced. Although this method is broadly applicable, we verify its performance in the breast at 3T where static magnetic field variations are substantial.

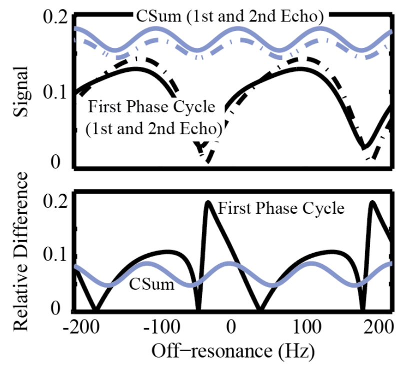

***Figure 1**. bSSFP signal profile of fat using a multi-peak fat model for the first echo (solid) and the second echo (dashed) for CSum and the first phase-cycle (top). (The second phase-cycle is just a shifted version of the first.) The difference between echoes relative to the maximum fat signal is fairly constant for CSum, but somewhat variable for individual phase cycles (bottom).*

Methods and Materials: A dual-echo bipolar readout 3D bSSFP pulse sequence was developed and used with phase-cycles of $\Delta\phi = 0°$ and $\Delta\phi = 180°$, providing two sets of images with shifted bSSFP profiles. Two different band reduction techniques were used to combine the separate phase-cycled images: First a 2-point Dixon fat/water reconstruction algorithm [8] is applied to each individual phase-cycle before combining phase-cycles for the water and fat images using a root sum-of-squares (RSOS) technique. Alternatively, due to the 90° phase-difference between phase-cycles in the pass band, a 2-point Dixon fat/water reconstruction algorithm can be performed on the complex sum (CSum) of both phase-cycles (essentially a two-point version of [6]). The use of a bipolar readout enabled the acquisition of the earliest available in-phase and opposed-phase echoes, enabling short TRs to reduce acquisition time. Bloch equation simulations, using a multiple-spectral-peak fat model [9], were used to determine echo and repetition times that would result in both good fat suppression and short scan times. This generally led to opposed-phase/in-phase TEs in the vicinity of 1.1 and 2.2 ms and TRs near 4.4 ms, although this may limit spatial resolution.

Volunteers were scanned on a 3T GE MR750 scanner. Parameters for the first two volunteers varied slightly around: matrix size = 224x256x66, resolution = 1.6x1.5x2 mm, and flip angle = 40° with two minute scan times. Data were collected with a TE1/TE2/TR = 1.1/2.2/4.4 ms and 1.4/2.5/4.8 ms for the first and second volunteer respectively. High-resolution data were collected for a third volunteer with TE1/TE2/TR = 1.1/2.2/4.4 ms, resolution = 1.1x1.1x1.6 mm, matrix size = 320x320x90, flip angle = 30°, bandwidth = ± 200 kHz, in 113s with a 2x parallel imaging acceleration. Images from the third volunteer were then interpolated to a through-plane resolution of 0.8 mm. Dixon fat/water separation was then performed for all datasets using both the RSOS and CSum methods.

Results: The bSSFP profile for the multi-peak fat model was simulated with TE1/TE2/TR = 1.1/2.2/4.4 ms at 3T and shown in Figure 1. We see that for the TE and TR values used, the shape of the profile is dependent on TE for the individual phase-cycle, while this effect is mitigated in the CSum profile. This is significant as the difference between the profiles appears in the water image, where the signal is much lower than the fat image. Figure 2 shows representative water images from the first two volunteers for both the CSum and RSOS methods along with each phase-cycle (the two images that are combined to form the RSOS image). In both volunteers we see that the fat suppression worked consistently well across both breasts for the CSum method. However, there are bands where fat suppression performs poorly in one or both of the phase-cycled images (dashed arrows). When the individual phase-cycles are combined to create the RSOS, the relative intensity of these bands can be reduced, but there is some residual, non-uniform fat signal. While the intensity of this effect varied as a function of off-resonance, this artifact appeared consistently in the RSOS images and was much less noticeable in the CSum images. We found that TE1/TE2/TR of 1.1/2.2/4.4 ms provided good fat/water separation and minimized the "india-ink" artifact at fat/water boundaries. Figure 3 shows high-resolution water images in the axial and sagittal reformat planes using the Csum method, with uniform fat suppression and near isotropic resolution.

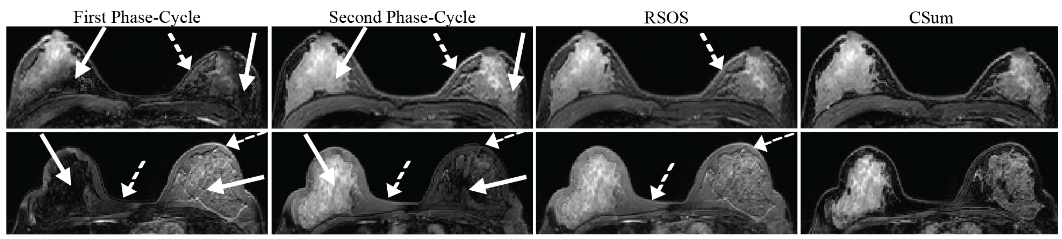

***Figure 2**. Representative water images from subject 1 (top) and subject 2 (bottom). Note that in the individual phase-cycle images there are regions where the fat suppression is poor (dashed arrows) in one or both of the phase-cycles and consequently the RSOS method. In the CSum images fat suppression is much more robust for the parameters chosen. Both the CSum and RSOS methods eliminate the banding in the water signal that is seen in an individual phase-cycle (see solid arrow).*

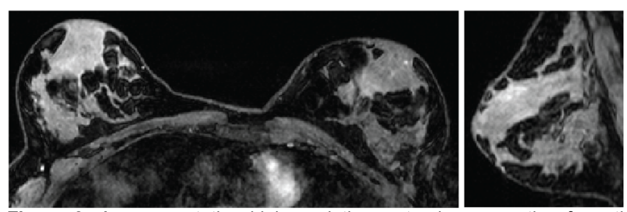

***Figure 3**. A representative high-resolution water image section from the CSum 3D bSSFP Dixon Sequence (left) and a sagittal reformat (right). Note the excellent spatial resolution of the reformatted image due to the near-isotropic scan resolution.*

Discussion: While the TE and TR values used in our images demonstrate the advantages of the CSum method, our Bloch simulations show that there are some TE and TR combinations for which the RSOS method should perform better. However, for clinically viable parameters this generally happens at higher TRs which lead to longer scan times. The complex sum approximates the magnitude and phase of an unbalanced gradient echo sequence, consequently the shape of the individual phase-cycle profile is more dependent on TR than the complex sum of the profiles. While we were able to demonstrate that our method enables robust fat suppression at higher field strengths, further analysis could provide additional insight into the optimal TEs and TR for both the RSOS and CSum methods.

Conclusion: The proposed dual-echo bipolar 3D bSSFP acquisition with a 2-point Dixon-based fat/water reconstruction works well at higher field strengths without any noticeable banding using the CSum method. This method provides higher resolution in shorter scan times than 2D FSE and could enable maximum intensity projections of the 3D bSSFP Dixon dataset to be used at 3T to explore the vasculature of the breasts without the need for Gadolinium contrast.

References: [1] Moran, JMRI 2009, 30:135-44 [2] Klifa, JMRI 2007, 25:82–8 [3] Saranathan, ISMRM 2010, p 769 [4] Huang, MRM 2004, 51(2):243-7 [5] Wieben, ISMRM 2005, p 2326 [6] Hargreaves *et al.* ISMRM 2006, p 1940 [7] Hwang, *et al.* ISMRM 2004, p 268 [8] Ma, MRM 2004, 52:415-419 [9] Ren, J Lipid Res. 2008, 49(9): 2055–2062