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Balanced SSFP Dixon Imaging with Banding-Artifact Reduction at 3T

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Abstract

Purpose—To develop a 3D balanced steady-state free-precession (bSSFP) two-point Dixon method with banding-artifact suppression to offer robust high-resolution 3D bright-fluid imaging.

Methods—A complex sum reconstruction that combines phase-cycled bSSFP images acquired at specific echo times for robust fat/water separation without banding was investigated and compared to a magnitude-based method. Bloch simulations using both single-peak and multiple-peak fat models were performed to predict the performance of these methods for a wide range of echo times (TE) and repetition times (TR). The quality and degree of fat/water separation was evaluated in both simulations and using in vivo imaging.

Results—Simulations predicted that both effective banding-artifact suppression and substantial improvements in fat/water separation are possible at echo times that are different from conventional echo times, enabling improved spatial resolution. Comparisons between various echo times and repetition times in vivo validated the improved fat/water separation and effective banding-artifact removal predicted by the simulations.

Conclusion—The proposed complex sum Dixon 3D bSSFP method is able to effectively separate fat and water at different sets of echo times, while removing banding-artifacts, providing a fast, high-resolution, T₂-like sequence without blurring.

Keywords

bSSFP; SSFP; fat suppression; steady-state; fat water separation; artifact reduction

INTRODUCTION

T₂-weighted imaging is a critical component of clinical imaging protocols, especially for visualization and characterization of fluid filled structures, lesions, and cysts. Due to their robustness and higher scan efficiency compared to conventional spin-echo sequences, RARE sequences (rapid acquisition with relaxation enhancement), also known as fast-spin-echo (FSE) or turbo-spin-echo (TSE), have been widely used for T₂-weighted imaging (1–3), typically with chemical fat suppression to improve visualization and lesion conspicuity.

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However, 2D RARE/FSE/TSE methods still suffer from long scan-times when contiguous coverage is desired, show tissue-dependent blurring, and have limited through-plane resolution.

Balanced steady-state free-precession (bSSFP) is a fast imaging sequence well known for its high SNR efficiency and T_2/T_1 contrast. However, it displays characteristic banding-artifacts in the presence of B_0 field inhomogeneity (4–9). The banding-artifacts can be arbitrarily shifted spatially by either modifying the excitation frequency or by adding a linearly increasing phase to successive excitations and readouts or “phase-cycling.” Sets of two or more separately shifted images can then be combined using complex sum, maximum intensity projection, or other combination techniques to produce banding-artifact-free images (9–14).

Fat suppression or fat/water separation is often helpful in the visualization of structures of interest such as tumors close to fat/water boundaries. Fat suppression in bSSFP can be accomplished through conventional fat-saturation methods (15,16), but such sequences are not robust to B_0 and B_1 heterogeneity. They also require a catalyzing sequence because the use of fat-saturation pulses disturbs the bSSFP steady-state. Alternatively, shifting or manipulating the banding to place the fat signal in the null of the banding profile during or after the acquisition can maintain a steady-state while suppressing fat (12,17–19), but is even more sensitive to B_0 variations. Fat/water separation in bSSFP has exploited the banding profile to retrospectively determine which signals come from fat and which come from water (20–23). Variations of the Dixon method (24) have also been shown to work well by exploiting the chemical shift between fat and water tissues and assuming a slowly varying B_0 field to provide robust fat/water separation. Specifically, a two-point Dixon technique has been shown to be compatible with bSSFP at 1.5T (25), although this method does not remove the banding-artifacts that are common at higher field-strengths. Additionally, Dixon techniques requiring three or more echoes, including the Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation (IDEAL) method, are compatible with bSSFP (26–29), but the acquisition of three or more echoes generally increases the TR, which increases scan time and exacerbates the banding issue. While the Dixon methods originally modeled the lipid resonance as a single-peak, it is in actuality a single dominant peak with several smaller peaks (30–37). Newer Dixon reconstruction methods have been shown to substantially improve fat/water separation at little cost by using a multiple-peak fat model in the reconstruction (32–35). Similarly, one would expect improvements in fat/water separation for methods that can utilize a multiple-peak fat model, particularly in bSSFP where the fat signal is a sum of fat peaks, each exhibiting a unique banding pattern. It should be noted that, while these methods have been shown to work for their various applications, most have not been extended to remove banding, and some require additional scan time for banding-artifact suppression, suffer from partial volume effects, or have varying levels of requirements on flip angle, TEs, TRs, and or phase-cycling patterns.

In this work, we present a novel complex sum two-point Dixon 3D bSSFP method with banding-artifact suppression that is capable of acquiring images with high-resolution in all dimensions. This method can provide T_2 -like contrast without blurring whilst incorporating

the robustness of the two-point Dixon method and addressing the banding-artifact issue endemic to bSSFP (38–40). Simulations were performed using a multiple-peak fat model to predict the performance and optimize the timing parameters for banding-artifact suppression and fat/water separation. The simulations led to choices of novel, non-obvious echo times to enable high-resolution imaging protocols. The performance of this method and the new echo times were then validated and compared to traditional echo times in breast imaging and imaging of the lower extremity (foot and knee). By optimizing the echo times, we were able to produce high-resolution images with T_2 -like contrast and enhanced fat/water separation in short scan times.

METHODS

Multiple-peak fat model in bSSFP

The standard bSSFP banding profile with phase-cycling increments of $\phi = 0^\circ$ and 180° , along with root-sum-of-squares and complex sum combinations of the two phase-cycled profiles can be seen in Figure 1. Note that both banding-artifact suppression schemes still have a slight ripple in the signal magnitude and that the complex sum combination maintains a phase that is roughly linear, thereby approximating an unbalanced gradient echo (GRE) sequence. In bSSFP, the multiple-peak fat profile itself is dependent on TE, TR, and off-resonant frequency as the fat peaks scale independently based on their banding pattern and relaxation parameters. We would therefore expect the performance of the fat/water separation to not only be dependent on the choice of TEs, but also on B_0 off-resonance and the choice of TR.

Reconstruction Methods

We investigated two methods of combined fat/water separation and banding-artifact suppression, which both rely on a modified two-point Dixon approach. Both methods require the acquisition of an in-phase and out-of-phase echo for both $\phi = 0^\circ$ and 180° phase-cycling schemes. They are named after their respective banding-artifact suppression schemes and are termed the root-sum-of-squares (RSOS) method and the complex sum (CSUM) Method. The RSOS method first performs a two-point Dixon reconstruction, creating a fat and water image for *both* phase-cycling schemes. The fat and water images from both phase-cycling schemes are then combined, using a root-sum-of-squares combination, to create one set of fat/water images with the banding-artifact suppressed. As the complex sum retains phase information, the CSUM method allows one to first produce banding-artifact suppressed in-phase and out-of-phase echoes by taking the complex sum of both phase-cycles for each respective echo. Fat and water are then separated with the two-point Dixon technique, creating one set of banding-artifact suppressed fat/water images. Figure 2 shows the simulated bSSFP signal profiles (using a 70% fat-fraction and the multiple-peak fat model described below, resulting in asymmetric signal profiles) as they progress through both reconstruction methods to form banding-artifact suppressed water and fat profiles.

Bloch Simulations

Bloch simulations were used to estimate the performance of the fat/water separation and banding-artifact suppression, using both single and multiple-peak fat models over a wide range of off-resonant frequencies, fat-fractions, excitation flip angles, and echo/repetition times. Glandular tissue parameters (see Supporting Table S1) were used as the “water” tissue to simulate the contrast we would expect to see in breast MRI. We simulated both the single-peak and multiple-peak fat models for all simulations. For the multiple-peak fat model, the relative weighting of each peak was extracted from breast and subcutaneous fat magnetic resonance spectroscopy (MRS) performed at 7T (36–37). The 7T relaxation constants were scaled to 3T values using the subcutaneous fat scaling factors reported by Jordan et al. (41). For one smaller peak that did not have a measured T_1 value (denoted by * in Supporting Table S1), T_1 was assigned to be a value that should be reasonable at 3T. The weighted average of the T_1 and T_2 values are 400 and 49 ms respectively, which is very close to the single-peak fat model used in our simulations and to those reported in literature (41–43). Simulation parameters used for the respective weighting, T_1 , and T_2 values for the peaks in each of the fat models as well as the water tissue are shown in Supporting Table S1.

Simulations were performed over a range of off-resonance values of $\pm 1/(2 \text{ TR})$, at a resolution of 1 Hz, spanning the entire range of off-resonant frequencies in the bSSFP profile. In order to ensure that fat/water separation performs well for multiple fat fractions, simulations using weighted sums of the water tissue and the fat tissue were performed for ten different fat-fractions evenly spaced and ranging from 0 to 100%. These data were simulated for a range of TEs from 0.7 to 4.5 ms and TRs from 3 to 7 ms, with a TE resolution of 0.02 ms and TR resolution of 0.05 ms. All TEs less than TR minus 0.1 ms were simulated for all TRs. The result is a simulation encompassing all possible combinations of fat models, off-resonance values, fat-fractions, and TEs for a given TR and flip angle.

Signals from all pairs of TEs for a given TR were then combined using both the CSUM and RSOS methods to perform fat/water separation. The use of all possible TEs/TRs creates combinations where fat and water might not be in and out-of-phase for portions of the banding profile. To account for this, the simulations for both methods used a known field map derived from the water tissue phase to minimize fat/water swaps at different off-resonance values. The outputs of this reconstruction are then the CSUM and RSOS fat and water signals simulated using both fat models, the full range of off-resonance values and fat-fractions, and all combinations of echo and repetition times.

In order to better visualize these multi-dimensional simulations, dimensions whose useful information could be reduced to a single value were identified and compressed. Both the off-resonance and fat-fraction dimensions were separately compressed to the single value that represented the worst-case fat/water separation across the entire dimension. Because the water image typically provides the majority of diagnostic information, we defined the worst-case error (WCE) or worst fat/water separation to be the maximum magnitude difference between the true water signal and the reconstructed water signal, relative to the maximum true water signal across all off-resonance values. The true water signal at a particular off-resonance value is given as the water signal reconstructed with a 0% fat-fraction.

Data were visualized in multiple ways to compare the different models, separation methods, and parameters. To compare the methods and models in our simulations, images were created displaying the WCEs computed using the range of echo times for a given TR, fat model, and separation method. In these images there were separate regions of echo times that had a low WCE and indicated ranges of echo times in which we could expect good fat/water separation within a given model and method. For a standard two-point Dixon spoiled GRE sequence at 3T, these ranges would lie around echo times of 1.2/2.3 ms, 2.3/3.5 ms, etc. These regions of low WCE were grouped into sets to compare the fat/water separation that we could expect within similar echo times and therefore similar restrictions on resolution, bandwidth, and imaging time. The first echo set range was the first region of low WCE where the first echo was at least 0.8 ms, which corresponded to the first echo that we could reasonably use to acquire a standard definition (256×256 matrix over 30cm FOV) image in a 3D Cartesian sequence. The second echo set range was then the set of echoes that formed the next distinct region of low WCE, and which permit more time to acquire higher spatial resolution than the first echo set. By comparing the WCE from different echo time combinations within the same set, we found the minimum worst-case error (MWCE) and the optimal echo times (defined as those echo times that minimize the WCE) for a given TR, model, method, and echo set. Plots were then generated showing the MWCE and optimal TEs as a function of TR for both fat models, separation methods, and for the first and second echo sets.

In Vivo Validation

In order to validate the simulations and assess the accuracy of each fat model, in vivo breast and lower extremity (foot and knee) images were acquired after informed consent and according to the guidelines of our Institutional Review Board (IRB). All images were acquired on a GE 3.0T MR750 scanner (GE Healthcare, Waukesha WI, USA). The parameters used for all in vivo images, including those from a high-resolution breast image, are shown in Table 1. The knee and foot images were acquired with a single-channel quadrature extremity coil (GE Healthcare, Waukesha WI, USA) while the breast images were acquired with a Sentinelle Vanguard 16-channel breast coil (Hologic Inc, Bedford MA, USA). For the breast and foot images, the first echo set accommodated both echoes in a bipolar readout while the second echo set acquired each echo in a separate TR (i.e., unipolar) to allow for higher spatial resolutions. The knee images utilized a unipolar readout for both echo sets to enable an easier comparison between the echo sets. When parallel imaging was used, data for all coils were first synthesized using the Auto-calibrating Reconstruction for Cartesian imaging (ARC) hybrid-space parallel imaging scheme (44). The images were then reconstructed using a custom C++ implementation of the region growing algorithm for two-point Dixon of Ma et al. (45), which separated fat and water for each coil separately before coil combination. Image reconstruction time varied between a couple of minutes to roughly two hours depending on the matrix size, parallel imaging configuration, and fat/water separation method used.

RESULTS

Multiple-peak fat model in bSSFP

The location and relative amplitudes of the multiple fat peaks are shown in Figure 3a along with a simulated, weighted sum free induction decay (FID) from those peaks displayed in Figure 3b. The un-weighted, bSSFP profiles from individual fat peaks as a function of off-resonance are shown in Figure 3c. In Figure 3d, the weighted fat peaks from three different off-resonance values are shown along with their combined FID from an individual phase-cycle and the complex sum of two phase-cycles (Fig. 3e). It is interesting to note that unlike other imaging sequences, the magnitude of the FID changes as a function of B_0 (or TR). While this is particularly true for the individual phase-cycled FIDs, there are also smaller, but noticeable differences in the complex sum FIDs.

Bloch Simulations

Simulations showed that both the CSUM and RSOS methods effectively suppressed the banding-artifact in the single-peak and multiple-peak fat models. The images showing the simulated CSUM and RSOS worst-case error of both fat models as a function of TE_1 verses TE_2 for a TR of 5.8 ms and flip angle of 35° are shown in Figure 4. Figure 5a–d shows the multiple-peak fat model MWCE, which is the minimum WCE over different TE sets for a given TR, as a function of TR for both separation methods and for the first and second echo set at multiple flip angles. The optimal echo times, which produce the MWCE, are then displayed in Figure 5e–h. Note that the single-peak fat model MWCEs are not shown in Figure 5 but they generally predict better fat/water separation.

The optimal echo times found using the multiple-peak fat model differ from those computed using the traditional single-peak fat model. For an individual phase-cycle, the primary fat peak will generally be in or out-of-phase at $TE=TR/2$. Therefore the optimal echo times for the RSOS method generally place one echo near $TR/2$ and the other roughly ± 1.15 ms apart. As the complex sum of two separate phase-cycles approximates an unbalanced gradient echo sequence, we would expect the CSUM method to have optimal echo times that are near multiples of 1.15 ms at 3T. Our simulations show that the single-peak fat model has optimal TEs that are almost exactly identical to these expected values. The multiple-peak fat model predicts optimal echo times that are close to the single-peak optimal echo times for the first echo set, but the predictions deviate considerably for the first echo of the second echo set. Specifically, for the CSUM method and multiple-peak fat model, the optimal echo times converge to approximately 2.7/3.5 ms, appreciably different from the 2.3/3.5 ms TEs derived using the single-peak model. Additionally, we see that the performance of the fat/water separation is dependent on both TR and flip angle for both methods and models, with higher variation at lower flip angles when using the CSUM method.

In Vivo Validation

The simulations and early in vivo images showed superior fat/water separation using the CSUM method when compared to the RSOS method. Additionally, we found that without a known B_0 field-map, the banding pattern in the individual phase-cycled images led to frequent fat/water swaps in the images before the root-sum-of-squares combination. This

was particularly apparent at TRs where the primary fat peak null was not aligned with the water null. Analysis therefore shifted primarily to assessing the performance of the CSUM method.

In order to demonstrate the quality of the fat/water separation commonly seen using the different methods, the CSUM water images at all TE combinations, a representative CSUM fat image, example RSOS fat and water images, along with the magnitude image from an individual phase-cycle of the knee are shown in Figure 6. The dashed arrows indicate a banding null in the fat tissue that led to a fat/water swap in the RSOS images as described above. While the CSUM water images exhibited varying levels of performance in fat/water separation, which is particularly apparent in the regions of visible fat banding indicated by the solid arrows, all were able to correctly identify fat and water, thereby avoiding fat/water swaps.

The banding pattern in the individual phase-cycled image of the foot indicates the presence of a significant and nearly linear off-resonance pattern in the proximal-distal direction of the foot. Figure 7 shows the banding pattern (dashed arrows) in the water image from an individual phase-cycle along with the water images from multiple TE combinations using the CSUM method in the foot. The banding-artifact suppression of this method is clearly visualized and, consistent with traditional complex sum and root-sum-of-squares combination schemes (13), a slight ripple is the only remnant artifact.

In Figure 8 the CSUM water images of the breast are shown for different TE and TR combinations. Figures 6–8 are labeled with the worst-case error predicted with the single-peak and multiple-peak fat models. In all instances, the banding-artifact suppression performed well and the multiple-peak fat model is able to estimate the performance of fat/water separation more accurately than the single-peak fat model. The solid arrows in Figures 6–8 indicate regions where fat/water separation is significantly worse for the non-optimal multiple-peak echo times than for the optimal multiple-peak echo times. In Figure 8, the dashed arrow points to a region which the optimal multiple-peak echo time images indicate to be adipose tissue, but could easily be mistaken for glandular tissue due to the poor fat/water separation of the 2.2/3.3 ms echo times (which were used because they represent the default two-point Dixon echo times on our vendor's product Dixon sequence). The dotted arrows in Figure 8 indicate the regions of poor fat/water separation that moved when a less optimal TR was used and modified the banding pattern. We note that although the images from the less optimal TR have superior fat/water separation in some regions (e.g., the region indicated by the solid arrows), the regions that do have poor fat/water separation at the less optimal TR have noticeably worse performance than the poor regions found at the more optimal TR. Axial slices along with a maximum intensity projection (MIP) of the high-resolution breast images are shown in Figure 9, which also portray excellent banding-artifact suppression and fat/water separation.

DISCUSSION

We have presented a novel CSUM method for fat/water separation and banding-artifact suppression in a 3D bSSFP sequence to provide T_2 -like contrast in short scan times.

Simulations were performed to find echo and repetition times that are mutually compatible with fat/water separation, banding-artifact suppression, and high-resolution imaging. In vivo scans of the knee, foot, and breast were then acquired to verify the method using parameters chosen from the simulations.

All of the in vivo images clearly show the improved validity of the error estimates using the multiple-peak fat model, as expected. While the simulations for the first echo set showed little difference between models, the significant improvement in fat/water separation for the images using the multiple-peak optimal echo times in the second echo set (which enables higher resolution) shows that the multiple-peak fat model more accurately predicts the performance of the fat/water separation.

While the CSUM method has been successfully demonstrated, it does have limitations that could restrict its usefulness in certain applications. Although this technique clearly suppresses the majority of the ripple, there is still a slight linear ripple visible in both the fat and water voxels of the CSUM water images of the foot. This slight ripple highlights the fact that this method may not be useful for quantitative imaging, as both the remaining bSSFP ripple and the imperfect fat/water separation inherent in two-point Dixon techniques can introduce errors. Additionally, while bSSFP techniques have been shown to provide T_2/T_1 -like contrast, in certain imaging scenarios the true T_2/T_1 contrast of bSSFP may require the acquisition of a T_1 -weighted image to remove T_1 effects.

Both the CSUM and RSOS reconstruction methods produce both a fat and water image. For voxels composed entirely of fat, the non-zero reconstructed water signal is actually fat that is not correctly separated. We therefore term this artifact residual fat, which, in our experience, is often one of the most noticeable separation artifacts both in simulations and in vivo. The magnitude of this effect as a function of repetition time is somewhat cyclical with a period of approximately 1.1 ms, indicating that the fluctuation is likely due to the relative banding pattern of the water and fat peaks.

It should be noted that the multiple-peak fat model does not indicate the echo pairs that put the fat and water signals perfectly in-phase and out-of-phase. While it seems intuitive that the signals should be perfectly in and out-of-phase at the optimal echo times, the simulations also account for the change in the signal magnitude as a function of echo time. The magnitude of the complex sum of the multiple-peak fat signal has little change between 1 and 2 ms, but becomes noticeably reduced between 2 and 3 ms (see Fig. 3e). This means that the first echo set will generally need to account for very little magnitude change. However, the second echo set can have the first echo before and the second echo after the signal drop. If these two echoes do place fat and water perfectly in and out-of-phase, then the fat signal magnitude difference between the first and second echo will appear as residual fat in the water image. If the first echo is delayed, the fat signal difference between echoes is reduced, leading to less residual fat. Consequently, the multiple-peak fat model simulations indicate optimal echo times that are not perfectly in-phase and out-of-phase, but rather specify echo times that balance the effects of both the signal magnitude and phase changes. The balance of these two potentially conflicting effects is part of the reason why the optimal

echo times of both fat models are similar for the first echo set and are noticeably different for the second echo set.

While the simulations for the CSUM method used on the multiple-peak fat model seem to predict echo times that minimize errors in the fat/water reconstruction, it is very difficult to determine what the actual error is in vivo. There are many factors such as off-resonance, B_1 inhomogeneity, fat-fraction, and proton density that cannot be known perfectly and make error quantification very difficult. This is particularly true in breast imaging at 3T, where substantial B_1 variation routinely causes the flip angle in the right breast to be approximately 40% greater than that of the left breast (46,47). While it is hard to quantify the error in vivo, fat/water swaps and obvious differences in the residual fat artifact seen in the in vivo images, demonstrate that the multiple-peak fat model simulations lead to non-obvious optimal echo times, which noticeably increase the performance of the fat/water separation.

Ma's two-point Dixon region-growing reconstruction was chosen for the two-point Dixon reconstruction primarily because of its robustness to off-resonance. While the method performed well, there are other two-point Dixon algorithms that would perform comparably well. Recent reconstruction methods have been developed for two-point Dixon acquisitions with arbitrary echo times (33–35). These methods utilize a multiple-peak fat model and B_0 off-resonance phase estimation in their signal equation for reconstruction. Their increased flexibility is expected to improve the performance of our proposed method. As the measured bSSFP fat peaks are a function of B_0 , these methods would potentially need to be modified to make the fat peaks dependent on off-resonance or alternatively could choose a static fat model based on some other criteria. Such methods could prove very effective, but are beyond the scope of this work.

While the image reconstruction time for our method was occasionally quite long, in part because of the need to process the images using both the CSUM and RSOS methods, it can be significantly shortened. Due to the CSUM method's similarity to standard two-point Dixon sequences, a new reconstruction pathway was developed which used vendor supplied software and hardware. While not employed in this work, this new reconstruction pathway was able to reconstruct high-resolution scans with high acceleration factors in less than ten minutes.

CONCLUSIONS

In summary, we have presented a novel two-point Dixon, 3D bSSFP sequence that simultaneously separates fat and water while removing the banding-artifact. Simulations led to the use of echo times that (a) were significantly different from those derived from a standard single-peak fat model and (b) improved the performance of fat/water separation at longer echo times, which also enabled high-resolution imaging. In vivo images in the knee, foot, and breast demonstrated the reliability of this method in regions of large B_0 inhomogeneity, where signal banding is particularly problematic for bSSFP at 3T. This method has potential to provide T_2 -like contrast in short scan times when clinical needs require high-resolution in all dimensions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIG. 1.

The characteristic bSSFP signal vs. frequency pattern for $T_1/T_2 = 1400/54$ ms and $TE/TR = 2.2/4.4$ ms, are shown for both the 0° phase-cycling increment (a) and the 180° phase-cycling increment (b). Two common banding-artifact suppression techniques are performed by either taking the complex sum (c) or the root-sum-of-squares (d) of both phase-cycling schemes. Note that the complex sum combination approximates the unbalanced gradient echo sequence, while the root-sum-of-squares combination removes all phase information.

FIG. 2.

The bSSFP signals vs. frequency simulated using a $\text{TE}_1/\text{TE}_2/\text{TR}$ of 1.1/2.2/4.4 ms, a flip angle of 35° , a 70% fat-fraction, and the water/multiple-peak fat models given in Supporting Table S1 are shown as they pass through the Complex Sum (CSUM) (a) and Root-Sum-of-Squares (RSOS) (b) reconstruction methods. Both methods start with bSSFP data from both 0° and 180° phase-cycling (PC) schemes and two separate TEs. The CSUM method first combines the individual phase-cycles by performing a complex sum to remove the banding. The remaining, band-free echoes are then processed using Ma's 2-point Dixon technique to create one water and fat image. The RSOS method first creates a water/fat image for each phase-cycle. The water images and the fat images are then each combined using a root-sum-of-squares combination to create a band-free water and fat image.

FIG. 3.

The spectral location and relative amplitudes of the fat peaks used in the multiple-peak fat model (a) and the GRE FID simulated by combining the weighted fat peaks (b). The unique shifting patterns of the unweighted bSSFP profiles of each fat peak are shown in c for a TR of 5.8 ms and a flip angle of 35°. Sampling and weighting each of the fat peaks at B_0 off-resonance values of -80, 20, and 120 Hz leads to the magnitude profiles in d along with the weighted, combined 0° phase-cycling and complex sum bSSFP FIDs (e). The 0° phase-

cycling FIDs clearly show variation in shape and amplitude at different B_0 off-resonances that are significantly reduced in the complex sum FIDs.

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FIG. 4.

The worst-case percent error versus the first and second echo time of both the single-peak (a, c) and multiple-peak (b, d) fat models for both the RSOS (a, b) and CSUM (c, d) reconstruction methods. The error was simulated using a flip angle of 35° and a TR of 5.8 ms. The single-peak fat model predicts very good fat/water separation over a larger range of echo times than the multiple-peak fat model. Furthermore, we see that for this choice of TR and flip angle, the CSUM method has regions of lower estimated error than the RSOS method.

FIG. 5.

The minimum worst-case error (MWCE) of the First and Second Echo Sets (FES/SES) for the RSOS and CSUM methods using the multiple-peak fat model are shown in a–d for flip angles of 20°, 30°, 40°, and 50°. The optimal echo times that produce the MWCE for each model and flip angle are shown in e–h. For flip angles above 30 degrees, the CSUM method generally predicts a better MWCE than the RSOS method for regions of TRs that predict a low MWCE.

FIG. 6.

CSUM water images of the knee at various echo time combinations (a–d) are shown along with the corresponding CSUM fat image (e), RSOS fat and water images (f, g), and the magnitude image from one of the individual phase-cycles (h). The solid arrows point to regions where a banding null in the individual phase-cycle image not only creates noticeable banding in the CSUM fat image (e), but also leads to worse fat/water separation in the CSUM water images when compared to the surrounding tissue. Dashed arrows indicate regions where banding nulls have led to fat/water swaps in the RSOS fat/water images. The CSUM method was found to generally lead to better fat/water separation and also to be far more robust to fat/water swaps. Additionally, the multiple-peak (MP) fat model was clearly able to predict the optimal echo time combinations (a, d) that exhibit the best fat/water separation.

FIG. 7.

A water foot image from an individual phase-cycle (a) shows the severe banding (dashed arrows) that indicate significant B_0 inhomogeneity. The corresponding CSUM water images (b–e), acquired at various echo times with a TR of 5.8 ms, show that the multiple-peak fat model is able to accurately predict echo pairs with improved fat/water separation (b, e). The solid arrows show bands of poor fat/water separation in the images for which the multiple-peak fat model predicts poor fat/water separation (c, d).

FIG. 8.

Axial (left) and Sagittal (right) CSUM water images of the breast at various echo times and repetition times, show that the multiple-peak (MP) fat model is able to more accurately predict TE/TR combinations with improved fat/water separation (a, b, e) than the single-peak (SP) fat model. As expected, the performance of the fat/water separation is dependent on B₀ variations (off-resonance). The dashed arrow indicates a region where the poor fat/water separation would have easily mistaken fat for glandular tissue. The solid arrows indicate a region of poor fat/water separation that is noticeably reduced at the optimal

TE/TR combinations. Dotted arrows point to regions of poor fat/water separation that were acquired at the optimal TE combination and a suboptimal TR (f). Not only do the locations of the poor fat/water separation change with TR, but the regions of poor fat/water separation are much more pronounced at the suboptimal TR.

Maximum Intensity Projection

FIG. 9.

High-resolution images of the breast acquired with optimized echo times at a resolution of $0.5 \times 0.5 \times 1.0 \text{ mm}^3$. (This resolution would be impossible at 1.2/2.2 ms echo times, and images would be degraded with 2.2/3.3 ms echo times.) Two separate axial slices are displayed (above) along with the Maximum Intensity Projection (below). The boxed portions have been zoomed in and are shown on the right of each image. The high resolution of the images clearly contributes to the fine details seen in the vasculature and the fibroglandular tissue of the breast.

Table 1

In Vivo Imaging Parameters

	Knee	Foot	Foot	Foot	Breast	Breast	High-resolution breast
Flip Angle	35°	35°	35°	35°	35°	35°	35°
Matrix Size	180×128×96	200×200×56	280×280×60	232×232×96	320×320×96	512×512×110	
FOV (cm ³)	27.0×20.3×19.2	28.0×28.0×9.0	28.0×28.0×9.0	32.0×32.0×15.4	32.0×32.0×15.4	25.6×25.6×11.0	
TE ₁ /TE ₂ /TR (ms)	1.2/2.2/5.8	1.2/2.2/5.8	2.2/3.3/5.8	1.2/2.2/3.8	2.2/3.3/5.8	2.7/3.5/6.1	
	2.2/3.3/5.8		2.4/3.5/5.8	1.2/2.2/5.8	2.4/3.5/5.8		
	2.4/3.5/5.8		2.7/3.5/5.8		2.7/3.5/5.8		
	2.7/3.5/5.8				2.7/3.5/6.4		
Readout type	unipolar	bipolar	unipolar	bipolar	unipolar	Unipolar	
Bandwidth	±100 kHz	±143 kHz	±143 kHz	±167 kHz	±143 kHz	±200 kHz	
Coil	extremity coil	extremity coil	extremity coil	16ch breast coil	16ch breast coil	16ch breast coil	
ARC Factor	N/A	N/A	N/A	2×1.25	2×1.25	2×1.75	
Acquisition Time	3:44	2:22	5:56	0:55, 1:24	3:44, 4:07	5:05	

In vivo images of the knee, foot, and breast were acquired with the parameters shown. In all imaging anatomies, multiple TE/TR combinations were used in order to validate the multiple-peak fat model and verify the performance of the method.