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Utilization of a Balanced SSFP Signal Model for Improved Fat/Water Decomposition

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Abstract

Purpose—Chemical shift based fat/water decomposition methods such as IDEAL are frequently used in challenging imaging environments with large B_0 inhomogeneity. However, they do not account for the signal modulations introduced by a balanced SSFP acquisition. Here we demonstrate improved performance when the bSSFP frequency response is properly incorporated into the multi-peak spectral fat model used in the decomposition process.

Theory—Balanced SSFP allows for rapid imaging but also introduces a characteristic frequency response featuring periodic nulls and pass bands. Fat spectral components in adjacent pass bands will experience bulk phase offsets and magnitude modulations that change the expected constructive and destructive interference between the fat spectral components.

Methods—A bSSFP signal model was incorporated into the fat / water decomposition process and used to generate images of a fat phantom, and bilateral breast and knee images in four normal volunteers at 1.5 Tesla.

Results—Incorporation of the bSSFP signal model into the decomposition process improved the performance of the fat/water decomposition.

Conclusion—Incorporation of this model allows rapid bSSFP imaging sequences to utilize robust fat/water decomposition methods such as IDEAL. While only one set of imaging parameters were presented, the method is compatible with any field strength or TR.

Keywords

balanced steady state free precession; fat-water imaging; IDEAL

Introduction

Chemical shift encoded (CSE) fat-water imaging techniques such as Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation (IDEAL)¹ have become increasingly popular in recent years due to their ability to robustly separate fat and water signals even in challenging imaging environments. This has enabled robust fat suppression in applications confounded by substantial B_0 heterogeneity, such as imaging involving a large field-of-view (FOV), extremities, and the bilateral breasts. IDEAL has successfully been applied to a wide variety of clinical imaging applications²⁻⁵.

Balanced Steady State Free Precession (bSSFP) imaging offers the ability to obtain high signal-to-noise ratio (SNR) images in short scan times⁶, making it an attractive choice for rapid imaging applications. Balanced SSFP has a unique, non-uniform spectral response featuring periodic pass bands separated by signal nulls at different off resonance frequencies⁶. Fat suppression methods have been developed to take advantage of this unique spectral response⁷⁻¹³. Several methods including Fluctuating Equilibrium MRI⁷, Oscillation SSFP¹⁰ and Alternating repetition time bSSFP¹³ modify the SSFP spectral response to suppress the signal from fat. Other methods of fat suppression in bSSFP imaging remove fat during post processing by taking advantage of the fact that with proper repetition time (TR) selection, fat and water will re-focus 180 degrees out of phase, such as SSFP with phase detection⁹ and Dixon based fat and water separation¹¹. Phase cycling schemes have also been incorporated to remove signal nulls caused by the bSSFP acquisition^{8,12}.

In CSE methods, a signal model of fat is utilized to predict the signal evolution at each echo time in the acquisition, allowing the fat signal to be separated from the water signal during post processing. Many CSE methods model the fat signal as a single spectral peak at ~3.3 ppm downfield from water (210 Hz at 1.5T). However, as fat contains multiple spectral peaks, a multi-peak model of fat allows for a more accurate prediction of the signal evolution, reducing fat leakage in the water images and reducing T1-bias in quantification applications¹⁴⁻¹⁷.

Emerging bSSFP fat-water imaging techniques aim to combine the rapid acquisition times achievable with bSSFP with the robust fat suppression provided by CSE fat-water decomposition methods¹⁸⁻²⁰. However, current implementations do not account for the combined effects of the multiple fat peaks and the frequency response of the bSSFP acquisition. This frequency response modulates the expected magnitude, and may change the sign of the expected phase of individual fat components depending on the spectral frequency offset of the component and the B_0 off resonance at that location. If this effect is not properly accounted for, water channel images will contain signal leakage from the fat channel, which may obscure clinically relevant features of interest.

In this paper we will (i) characterize these errors using simulations and phantom experiments, and (ii) develop and provide preliminary in vivo validation of a signal modeling based reconstruction approach for addressing this effect. Here, CSE fat-water decomposition is performed using a multipeak fat model that also incorporates the off-resonance amplitude and phase modulations resulting from the bSSFP frequency response. While the fat signal model in conventional CSE fat-water imaging does not vary during the iterative algorithm, this approach recalculates the fat signal model during each iteration to account for signal changes as the B_0 fieldmap estimate is refined. The benefits of the approach are demonstrated in bilateral breast and knee imaging.

Theory

The ability of CSE fat-water decomposition methods to remove the undesired fat signal depends on accurately modeling the signals arising from fat. As described in Reeder et al.¹⁶ and Yu et al.¹⁴, fat contains multiple ^1H peaks that can be more accurately represented using a multipeak model. Fat has been modeled as a series of discrete peaks consisting of the methylene peak at 3.3 ppm with up to five additional peaks¹⁴⁻¹⁷. In standard multipeak models of fat, each of the fat spectral components accrue phase relative to a reference point, T_{ref} , which is the midpoint of the radiofrequency (RF) pulse for gradient echo imaging or the echo time (TE) for spin echo imaging. These components combine constructively or destructively over the course of the repetition time (TR), producing a complex response over time. The effects of B_0 inhomogeneity are modeled as linear phase shifts applied to each of the spectral components at each echo time. Using this model, CSE fat-water techniques have been used for many applications using both gradient and spin echo acquisitions^{1,16,21,22}.

Balanced SSFP produces a characteristic frequency response featuring periodic nulls and passbands as determined by the TR, flip angle, and T1 and T2 values of the tissue present. Each spectral component will experience some degree of magnitude modulation depending upon the location of its off resonance frequency within the bSSFP pass band as shown in Figure 1. In addition to the magnitude modulation, spectral components placed in adjacent pass bands due to the length of the TR will, in general, experience a phase inversion as illustrated in Figure 1d. The expected magnitude and phase based on the off resonance frequency can be calculated as described below in *Equation 1*.

In standard bSSFP imaging, as in spin echo imaging, signal acquisition is often centered over the refocusing point T_{ref} , where $T_{\text{ref}} = \text{TR}/2$. If the TR is selected such that all fat spectral components are contained within one pass band, all fat signal will refocus in phase at T_{ref} as in spin-echo imaging (Figure 1b, c). However, achieving feasible TRs with even modest resolution requires narrower pass bands that place the fat spectral components in two or more adjacent pass bands (Figure 1d-f). Spectral components placed in adjacent pass bands experience a π phase offset at $t = T_{\text{ref}}$ as shown in Figure 1d. While one might expect fat signal amplitude to be a maximum at the refocusing point of $\text{TR}/2$, destructive interference between fat components leads to a drop in magnitude at the refocusing point, as shown in Figure 1e. If this behavior is not correctly modeled, a portion of the fat signal will be improperly assigned to the water channel during image reconstruction.

Just as TR selection impacts the width and spacing of bSSFP pass bands and thereby changes the expected fat signal, the presence of B_0 inhomogeneity will also modulate the final fat signal. In bSSFP imaging, a large frequency offset will shift individual spectral components from one pass band to another, causing a phase inversion in the shifted components and a rapid oscillation in the expected signal magnitude as a function of B_0 offset as demonstrated in Figure 2.

In most chemical shift based decomposition methods, the expected magnitude and phase response can be calculated once and then a phase shift applied to account for any B_0 offset. Due to the magnitude and phase dependence on the bSSFP frequency response, an accurate signal model requires the expected magnitude and phase of fat to be calculated separately over a range of likely B_0 offsets. The bSSFP steady state signal equation can be derived from the Bloch equations and is presented in Zur et. al. 1988²³ as:

$$M_{ss} = \frac{a \exp(i\varphi) + b}{c \cos \varphi + d} \quad \text{Equation 1}$$

where $\varphi = 2\pi TR(f_p + f_m)$ is the precession angle, θ is the flip angle, f_p is the off resonance value of the current spectral component, f_m is the off resonance due to B_0 inhomogeneity, $a = -(1 - E_1)E_2 \sin \theta$, $b = (1 - E_1) \sin \theta$, $c = E_2(E_1 - 1)(1 + \cos \theta)$, $d = 1 - E_1 \cos \theta - (E_1 - \cos \theta) E_2^2$, $E_1 = \exp(-TR/T_1)$ and $E_2 = \exp(-TR/T_2)$.

The bSSFP signal model is the summation of the magnitude and phase profile for each fat spectral component determined using *Equation 1* with a phase shift of $2\pi TE(f_p + f_m)$ applied as shown in *Equation 2*:

$$S = \exp(i2\pi f_m TE) \left(\rho_W M_{ss}(f_w, f_m) + \rho_F \sum_{p=1}^P M_{ss}(f_p, f_m) \exp(i2\pi f_p TE) \right) \quad \text{Equation 2}$$

Where ρ_W and ρ_F are the amplitudes of the fat and water components respectively, $M_{ss}(f_p, f_m)$ is the bSSFP steady state signal equation given in *Equation 1*, and $f_w = 0$ is the off resonance value of water. This model is used to produce the theoretical signal at each echo time and calculated for all possible B_0 values. This B_0 dependent signal model is incorporated into the iterative fat/water decomposition algorithm. Refer to Figure 1 (a and d) for theoretical computation.

Methods

bSSFP Signal Model and Fat/Water Decomposition

The bSSFP signal model described in *Equations 1* and *2* was incorporated into the fat-water decomposition process. The fat signal was modeled as six peaks as described by Yu et al¹⁴ with relative amplitudes in decreasing order of 0.62, 0.15, 0.1, 0.06, 0.03, and 0.004 and corresponding peaks at 210, 159, -47, 236, 117 and 23 Hz at 1.5 T as illustrated in the stem plot in Figure 2a. The fat-water decomposition was accomplished using a technique for B_0

fieldmap estimation including smoothness constraints and solved using a graph-cut iterative algorithm²⁴.

Echo Selection

The specific echo times (TE) selected impact the achievable noise performance in CSE fat-water separation techniques. As described in Glover 1991. This can be described using the effective number of signal averages (NSA)²⁵⁻²⁷:

$$NSA = \frac{\sigma^2}{\sigma_\rho^2} \quad \text{Equation 3}$$

Where σ^2 is the variance of the noise in a source image and σ_ρ^2 is the variance of the noise in the fat or water separated image. Imaging at the reference point when water and fat are in phase has been shown to limit the achievable NSA performance and cause imaging artifacts when acquiring three echoes for CSE fat-water imaging^{1,28}. This may or may not be of concern in a three-echo bSSFP acquisition depending upon the location of the water and primary fat peak within the pass band as determined by the selection of TR. If water and the primary fat peak are in the same pass band or separated by an odd number of pass bands, the fat and water signal will align in phase at T_{ref} and experience this effect. However, if the fat and water are in adjacent pass bands or separated by an even number of pass bands, the signals will align out of phase at T_{ref} and this will have no impact²⁸.

Placing a conventional Cartesian readout within a bSSFP sequence for conventional CSE fat-water imaging requires at least three passes through k-space while lengthening the TR to allow for at least three echo times. While this type of acquisition is compatible with the bSSFP fat model presented in this work, it limits the time available to acquire high-resolution images. Instead, a rapid acquisition was achieved using a 3D-radial Vastly undersampled Isotropic Projection Reconstruction (VIPR) pulse sequence^{20,29}. The out-and-back radial trajectory produces two unique half echoes every TR while completely re-winding the magnetization as required for bSSFP imaging. As described in Moran et. al.²⁰, data collection is split into two passes temporally shifted from one another to produce four echo times, each consisting of a unique set of radial lines which allows for higher achievable resolution and reduces the appearance of streak artifact due to undersampling. The four echoes acquired by the VIPR trajectory allow for more flexibility in the selection of the echo timing without compromising the noise performance³⁰. A TR of 4.6 ms was selected to allow for the collection of the four half echoes while keeping the primary fat peak and water centered in adjacent pass bands, allowing the largest levels of off-resonance to be present before bSSFP nulls are introduced into the image. An NSA analysis was performed to determine the optimal echo times that were also compatible with the dual pass, out and back radial sampling trajectory of VIPR. Optimal echo times were found to be 0.5, 1.4, 2.7 and 3.6 ms.

Phantom Experiments

A phantom consisting of peanut oil was imaged on a clinical 1.5T Scanner (Signa HDxt 1.5 T, GE Healthcare, Waukesha WI) using an 8-channel, receive only head coil (GE Healthcare, Waukesha WI). A shim was applied during imaging to generate offsets in the main magnetic field of ± 500 Hz across the horizontal dimension of the phantom. The phantom was imaged using the bSSFP VIPR acquisition. Imaging parameters were as follows: 18 cm FOV, 80,000 radial projections, 288 isotropic imaging matrix, 15 degree flip angle, bandwidth of ± 83.33 kHz, and 4.6 ms TR. Decomposition was performed using the proposed bSSFP signal model as well as the standard spin echo multipeak fat model¹⁴ utilizing and externally generated fieldmap.

In-Vivo Imaging

Breast and knee volunteers were imaged with the multi echo bSSFP VIPR acquisition on a 1.5 T clinical scanner (Optima 450w, GE Healthcare, Waukesha WI) using an 8-channel breast array (GE Healthcare, Waukesha WI) or an 8-channel transmit/receive knee array (Invivo, Orlando FL) respectively during an IRB approved, HIPAA compliant study. Bilateral breast scans were performed with an axial slab excitation and a 36 cm FOV. 66,000 radial projections were collected to reconstruct a 576 isotropic image matrix with 0.62 mm isotropic spatial resolution in a five minute scan time. Shim volumes were placed over each breast such that the calculated linear shim and center frequency settings did not consider tissue between the breasts. The knee exams also utilized an axial excitation and acquired 66,000 radial projections in a five-minute scan time. An 18cm FOV and 384 isotropic imaging matrix were utilized to produce 0.46 mm isotropic resolution. For comparison purposes, volunteers were also imaged with a 3D radial VIPR implementation of the Alternating Repetition time (aTR) bSSFP sequence¹³. Imaging parameters including FOV, number of projections and imaging matrix size were held constant between the multi echo bSSFP VIPR and the VIPR aTR except for the imaging matrix size in the breast volunteers, which was reduced to 512 (0.7mm isotropic resolution) to accommodate the TR length requirements of the aTR sequence. For the multi-echo bSSFP VIPR reconstructions, decomposition of the fat and water signal was performed offline using a MATLAB (MATLAB Release 2011b, The MathWorks, Inc., Nantick MA) implementation of the graph cut iterative algorithm²⁴. The T1 and T2 values of 296 ms and 53.33 ms for breast adipose tissue were obtained from the literature³¹ and used in the bSSFP signal model.

Results

Phantom Experiments

Application of the linear shim to the peanut oil phantom imaged using a bSSFP acquisition creates periodic magnitude oscillations due to constructive and destructive interference of the different fat spectral components at various B_0 offset frequencies (Figure 3b, c) as predicted by the bSSFP signal model (Figure 3a). Fat/water decomposition performed using the standard spin echo multipeak fat model fails to account for the signal modulations present in the bSSFP acquisition, resulting in periodic variations of the signal in the final fat image (Figure 3d) as well as undesired signal leakage into the water channel (Figure 3e). Due to the large field-offsets generated by the applied shim and plastic/water interfaces of

the phantom, errors exist in the fieldmap we utilized (yellow arrows). Numerous methods have been presented in the literature to handle these difficulties, but fieldmap generation is not a focus of this work.

The measured fat signal at different off-resonance field offset values closely aligns with the signal predicted by the bSSFP signal model as shown in Figure 3 (a and b). Measurements were performed at four different echo times; the exact pattern of the magnitude oscillations observed changes with echo times as different spectral components align in-phase and out-of-phase over the course of the TR. Increasing signal magnitude with increasingly negative linear shim offsets across all measured echo times is also observed (Figure 3b) but is unrelated to the bSSFP acquisition and is instead due to the close proximity of the phantom to the surface coil array. Incorporating the bSSFP signal model presented in this work into the fat-water decomposition process reduces the observed signal oscillations and results in a more uniform signal decomposition as depicted in Figure 3 (f and g). Except in the immediate vicinity of the nulls, the fat channel (Figure 3f) displays uniform fat signal intensity while the water channel shows uniform suppression of fat (Figure 3g). The amplitude difference between echoes is also due to differences in constructive or destructive interference between the different fat spectral components at each echo time.

In-Vivo Imaging

Figures 4 and 5 show the results of VIPR aTR and bSSFP VIPR decomposed using the bSSFP signal model in the breast and the knee respectively. The bSSFP signal model water images show apparently complete suppression of the fat in the breast while the aTR images suffer from partial fat suppression. In the knee, the bSSFP signal model decomposition displays greatly improved fat suppression in the subcutaneous fat and moderately better suppression in the bone as compared to aTR. Signal from fluid around the knee joint appears brighter in the aTR images than in the images produced using the bSSFP signal model.

Discussion

We demonstrate that bright fat signal produced by a bSSFP excitation can be reliably separated from water signal using CSE fat-water decomposition techniques when a proper bSSFP signal model is incorporated. This signal model is applicable to any bSSFP imaging application where fat-water separation is desired in which the bSSFP and fat-water acquisition timing requirements can be met. As shown in Figures 4 and 5, the incorporation of the bSSFP signal model greatly improves the fat/water decomposition resulting in near complete suppression of the fat signal in the water channel images. This improves the contrast between the fat and the features of interest in the water channel.

Figures 4 and 5 display imaging results from the aTR¹³ fat suppression method. This is a bSSFP method that works through a combination of phase-cycling and alternating TR times chosen such that TR1:TR2 is 3:1, or TR1 = 3.47 ms and TR2 = 1.15 ms at 1.5T, to place a large signal null over the large methylene peak. However the suppression is incomplete, allowing some residual fat signal to leak into the final images as seen in Figures 4 and 5. The specific TR timing requirements can also limit the achievable resolution. Data acquisition takes place during the first TR and was adequate to achieve 0.46 mm isotropic resolution in

the knee. A much larger imaging matrix (576 x 576 x 576) was used to image the bilateral breasts using the bSSFP VIPR acquisition with fat suppression provided by the bSSFP signal model. There was insufficient time to sample this matrix size in the TR1 of aTR, forcing the imaging matrix to be reduced in size to 512 x 512 x 512. Due to this lower resolution and poorer fat suppression, the aTR breast images look slightly blurred in comparison to the bSSFP signal model images.

The bSSFP signal model described in this work requires several assumptions about the imaging environment, including T1 and T2 relaxation values of fat and the flip angle. As described above, these parameters will determine the shape of the modeled bSSFP frequency response used to create the bSSFP frequency model. Because of this, care should be taken in selecting reasonable T1 and T2 values for the fat tissue. As the T1 and T2 values of fat tissue are relatively unaffected by gadolinium based contrast agents, this method should be unaffected by the presence of contrast agent but further work is needed to verify this. In this work, literature values of T1 and T2 for breast adipose tissue were used in modeling the signal for both the breast (Figure 4) and the knee (Figure 5), producing good results in both cases. Similar mismatches can occur due to inhomogeneities in the B_1 field. Signal leakage due to mismatches between the model values and the actual tissue values will be most apparent when one of the larger fat frequency components is approaching a signal null, as this is where the magnitude profile is changing most rapidly.

This description has focused on the scenario where the water peak and the primary fat peak are centered in adjacent pass bands, such as occurs at 1.5T with a TR of 4.6 ms. However, as the TR or the magnetic field strength change, the expected behavior of the fat signal will also change as the individual spectral components are shifted into different pass bands. For example, at 3T with a TR of 4.6 ms, the passbands containing the primary fat peak and the water peak would be separated by one passband. Water and fat will be in phase at the reference point, resulting in phase behavior similar to that of a spin echo sequence. However, this will also place the secondary fat spectral component (peak 2 in Figure 2a) in close proximity to a null when the B_0 offset is near zero. Relatively small changes in the B_0 field will cause this peak to alternate between passbands, resulting in fairly large magnitude oscillations in the fat signal. Correct modeling of this situation, as provided by the method proposed here, is important to prevent signal leakage into the water channel.

While utilizing a multipeak model of fat should allow for a more accurate decomposition of the fat and water signal as described above, a simpler single peak model could also be used. Since the model can predict whether fat or water will be in phase or out of phase and the phase evolution over the course of the TR, the constraints on the choice of TR imposed by other methods^{9,11}, generally that fat and water must refocus out of phase at TR/2, and it allows echoes to be acquired at times other than TR/2. This flexibility can more easily accommodate the demands of high resolution imaging such as the 0.6 mm isotropic resolution breast images shown here in Figure 4. As with other CSE methods, there is a loss of scan time efficiency when multiple echo times must be acquired, but that is partially alleviated here by the use of the 3D radial VIPR trajectory that acquires two echoes per TR.

The bSSFP frequency response also results in nonlinear fat signal behavior compared with spin echo or gradient echo sequences. The graph-cuts algorithm utilized for the fat/water decomposition is well-suited to handle the nonlinearities as it solves for the fieldmap at all voxels simultaneously, which makes it less likely to converge upon the wrong local minima as seen with voxel based fat-water decomposition methods²⁴. However, further refinements to the fieldmap estimation would make it more robust to artifacts when combined with the bSSFP signal model. Signal leakage is seen in the immediate vicinity of the nulls due to rapid changes in expected magnitude in these areas, making even small errors in calculated fieldmap impact decomposition quality.

Conclusion

We have demonstrated how incorporating a bSSFP signal model into a chemical shift based fat-water decomposition method can improve the quality of the fat/water decomposition. While the methods here focused on 1.5T and a fixed TR of 4.6 ms, the model is applicable to other field strengths and repetition times. When combined with a rapid acquisition technique such as the radial out and back radial trajectory used in VIPR, this method allows for high resolution T2 like imaging with robust fat/water separation even in areas with large field offsets such as in bilateral breast imaging.

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Figure 1.

Theoretical water and multipeak fat spectral components along with bSSFP magnitude and phase response modeled for an echo time of $TR/2$ and TR s of 1.5ms (a) and 4.6 ms (d) at 1.5T. Placement of individual fat components in adjacent pass bands results in phase inversion and destructive interference between fat components leading to a signal minima at the bSSFP refocusing point $T_{ref}=TR/2$. The resulting magnitude (b and e) and phase (c, f) behavior of the bSSFP signal (red) over time, plotted such that $t=0$ at the refocusing point T_{ref} , is highly dependent upon the location of the fat components within the bands and can be very similar (b and c) or very distinct (e and f) from the spin echo (green) imaging more commonly used in fat / water decomposition depending on the TR selected.

Figure 2.

Water and fat spectral components labeled in order of decreasing magnitude, along with bSSFP magnitude and phase response for 1.5 T and 4.6 ms TR (a). Magnitude (b) and phase (c) responses vs. B_0 off resonance for an echo time of 1.9 ms. Numbered arrows in (b) and (c) indicate the large oscillations that occur as the corresponding fat spectral peaks undergo phase inversion after shifting between adjacent pass bands. The phase response (c) is dominated by the primary fat component, while the magnitude response (b) is sensitive to both shifts in the primary peak as well as the secondary peaks due to destructive interference of the resulting signal.

Figure 3.

bSSFP signal model predicted (a) and measured (b) magnitude for the peanut oil phantom with a linear shim applied (c) imaged at 1.5 T with a TR of 4.6 ms and echo times of 0.5, 1.36, 2.71 and 3.56 ms. Fat / Water decomposition performed using the standard spin echo model of fat (d, e) or the bSSFP model (f, g) and an externally generated fieldmap. Oscillations due to constructive and destructive interference between different spectral peaks is predicted by the model (a) and observed in the measured data (b, c). The fat channel image produced using a standard signal model (d) retains the intensity variations as well as signal voids due to bSSFP nulls. Signal leakage into the water channel is seen due to mismatch between the standard signal model and the bSSFP signal (d and e, white arrows). The fat and water images produced using the bSSFP model demonstrates fairly uniform signal intensity and suppression respectively except in the immediate vicinity of the bSSFP nulls (f and g, white arrow heads). Signal leakage is seen in the water channel in both decompositions due to errors in the supplied fieldmap (small yellow arrows).

Figure 4.

VIPR aTR (a-c) and bSSFP VIPR water channel images produced by the bSSFP model decomposition (e-f) of the bilateral breasts with 0.70 mm and 0.62 mm isotropic resolution respectively. Full acquired axial field of view (a, d) as well as sagittal (b, e) and coronal (c, f) reformatted images. The bSSFP VIPR images display complete fat suppression across the imaging volume while the aTR images suffer from incomplete fat suppression.

Figure 5. VIPR aTR (a-c) and bSSFP VIPR model water (d-f) channel images of the knee with 0.46 mm isotropic resolution acquired in the axial (a, d) plane and reformatted into the coronal (b, e) and sagittal (c, f) planes. The bSSFP signal model provides more complete fat suppression in the subcutaneous fat and in the bone.