Enhanced Phase-Sensitive SSFP Reconstruction for Fat-Water Separation in Phased-Array Acquisitions

Ozgur Yilmaz, BS,1,2 Emine Ulku Saritas, PhD,1,2,3 and Tolga Çukur, PhD1,2,3*

Purpose: To propose and assess a method to improve the reliability of phase-sensitive fat–water separation for phased-array balanced steady-state free precession (bSSFP) acquisitions. Phase-sensitive steady-state free precession (PS-SSFP) is an efficient fat–water separation technique that detects the phase difference between neighboring bands in the bSSFP magnetization profile. However, large spatial variations in the sensitivity profiles of phased-array coils can lead to noisy phase estimates away from the coil centers, compromising tissue classification.

Materials and Methods: We first perform region-growing phase correction in individual coil images via unsupervised selection of a fat-voxel seed near the peak of each coil’s sensitivity profile. We then use an optimal linear combination of phase-corrected images to segregate fat and water signals. The proposed method was demonstrated on noncontrast-enhanced SSFP angiograms of the thigh, lower leg, and foot acquired at 1.5T using an 8-channel coil. Individual coil PS-SSFP with a common seed selection for all coils, individual coil PS-SSFP with coil-wise seed selection, PS-SSFP after coil combination, and IDEAL reconstructions were also performed. Water images reconstructed via PS-SSFP methods were compared in terms of the level of fat suppression and the similarity to reference IDEAL images (signed-rank test).

Results: While tissue misclassification was broadly evident across regular PS-SSFP images, the proposed method achieved significantly higher levels of fat suppression ($P < 0.005$) and increased similarity to reference IDEAL images ($P < 0.005$).

Conclusion: The proposed method enhances fat–water separation in phased-array acquisitions by producing improved phase estimates across the imaging volume.

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Balanced Steady-State Free Precession (bSSFP) sequences typically generate relatively higher levels of signal from fat when compared to water tissues. However, separation of these two resonances is critical for many applications including cartilage imaging, abdominal imaging, and angiography. Among the approaches proposed to address this problem were steady-state techniques that reshape magnetization profiles, techniques that temporarily alter transient signal profiles, and Dixon-type techniques that rely on multiple acquisitions to separate the two resonances. Because the above techniques either suppress fat signals during acquisition or perform subvoxel fat–water decomposition based on multiple signal measurements, they can offer reduced sensitivity to partial volume effects. At the same time, however, these techniques require pulse sequence modifcations and multiple echoes or acquisitions that usually prolong scan times.

Phase-sensitive SSFP (PS-SSFP) is a scan-time-efficient alternative for fat–water separation that does not require modification of standard bSSFP sequences. PS-SSFP generates out-of-phase fat and water signals by placing their respective resonances in neighboring bSSFP passbands. Following a correction for additional slow-varying phase components due to inadvertent factors such as field inhomogeneity and coil sensitivity, PS-SSFP leverages abrupt phase changes arising near fat–water boundaries to separate the two signals. However, residual phase variations that remain in corrected images can cause suboptimal fat–water separation.

PS-SSFP reconstructions have been previously demonstrated to work reliably on images acquired with quadrature.

*Address reprint requests to: T.C., Department of Electrical and Electronics Engineering, Bilkent University, Ankara, TR-06800, Turkey. E-mail: cukur@ee.bilkent.edu.tr

From the 1Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey; 2National Magnetic Resonance Research Center, Bilkent University, Ankara, Turkey; and 3Neuroscience Program, Bilkent University, Ankara, Turkey

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via an unsupervised seed-selection procedure, to enhance tis-
with phased-array coils. The specific aims of this study were 
phase-sensitive fat–water separation in bSSFP images acquired 
factors.

Here we propose and assess an improved strategy for 
phase-sensitive fat–water separation in bSSFP images acquired 
with phased-array coils. The specific aims of this study were 
to improve the accuracy of region-growing phase correction 
via an unsupervised seed-selection procedure, to enhance tissue 
classification by optimally aggregating phase information 
across individual-coil images, and finally to demonstrate the 
performance of the proposed strategy in vivo on bSSFP 
angiograms acquired in the lower extremities.

Materials and Methods

Dual-Acquisition PS-SSFP Reconstruction

The PS-SSFP approach relies on the frequency dependence of 
bSSFP magnetization profiles.15 Balanced SSFP sequences generate 
periodic magnetization profiles, with \( \pi \)-radians phase difference 
between consecutive passbands (Fig. 1a). Therefore, a \( \Delta \phi = \pi \) 
phase-cycled bSSFP sequence can produce out-of-phase images 
when the repetition time (TR) is selected to place fat and water 
resonances an odd number of passbands apart, TR = \((2n+1)\Delta f \)
where \( n \) is an integer and \( \Delta f \) is the fat–water frequency difference 
(eg, TR = 4.6 msec at 1.5T). To improve immunity against off-
resonance while maintaining this phase difference, dual-acquisition 
PS-SSFP16 acquires a separate \( \Delta \phi = 0 \) phase-cycled bSSFP image, 
and complex sums the \( \Delta \phi = \pi \) and \( \Delta \phi = 0 \) images (Fig. 1a). The 
acquired signal can be expressed as:

\[
S(r) = |W(r) - F(r)| \cdot e^{-j\Theta(r)}
\]

where \( r \) is the spatial location, \( W \) is the level of water signal, \( F \) is 
the level of fat signal, and \( \Theta \) denotes the spatially varying image phase due to various sources including field inhomogeneity, susceptibility, and coil sensitivity.

PS-SSFP assumes that each voxel contains dominantly fat or water tissue, and that \( \Theta(r) \) is distinguishable from the rapid phase shifts near fat–water boundaries. In such cases, a region-growing phase-correction can be applied to remove the slowly varying phase component, \( \Theta(r) \). In the current study, we use the correction algorithm proposed by Hargreaves et al.19 This algorithm first splits the imaging volume into small blocks (eg, \( 6 \times 6 \times 6 \) voxels). Starting with a seed block, it updates the block phases by \( \pi \)-radians when necessary, such that the intensity-weighted sum of block phases varies smoothly across the image. Following correction of the images for the estimated block phases, phase-sensitive fat–water separation is performed.

The reliability of PS-SSFP can be compromised by rapid phase variations that violate the assumption of gradually varying \( \Theta(r) \). Unlike quadrature coils with broad spatial coverage, phased-
array coils typically introduce large phase variations away from the coil centers where the individual-coil sensitivity diminishes. To demonstrate typical differences in image phase between quadrature-
coil and phased-array data, we acquired bSSFP images of the lower leg with TR = 9.2 msec at 1.5T using both a quadrature coil and a receive-only 8-channel phased-array coil. This TR selection—an even multiple of the ideal TR—places fat and water resonances 
two passbands apart, and thus the resulting tissue signals are in phase. The distributions of voxel magnitude and phase across in-
phase bSSFP images were visualized (Fig. 1b). As expected, voxel phases are much more broadly spread and variable in a phased-
array coil compared to a quadrature-coil. These excessive phase var-
ations in turn increase the possibility of fat–water misclassification 
in phased-array bSSFP acquisitions.

PS-SSFP for Phased-Array Acquisitions

We propose a strategy to improve phase-sensitive reconstructions of 
bSSFP data acquired with phased-array coils. In regular PS-SSFP, a 
central voxel is selected as the starting seed for region-growing 
phase correction.15 A single, common seed can be designated for 
all coils to prevent global phase inconsistencies among coils.2 However, in coils for which the starting seed is relatively distant to the 
peak sensitivity region, this procedure can cause suboptimal phase 
correction and fat–water swaps in subsequent reconstructions. To 
address this issue, we propose an unsupervised technique for coil-
wise seed selection (Fig. 2a). This technique first reconstructs a 
low-resolution image for each coil by Fourier transforming the central 4% of k-space data. The coil-sensitivity profiles \( (C_\text{coil}) \) are then taken as the ratio of these individual-coil images to the sum-
of-squares combination of low-resolution images across coils.19 
Note that fat typically yields much higher bSSFP signals than water 
tissues in the lower extremities considered here.20 A fat-voxel seed 
can thus be selected based on signal intensity. However, since tissue 
boundaries may be blurred in low-resolution sensitivity profiles, 
the sensitivity peak may correspond to a water or background voxel 
neighboring a high-intensity fat voxel. For this reason, the sensitivity 
profile is multiplied with the magnitude of the respective full-
resolution coil image prior to selection. The voxel that maximizes 
this product is then designated as the seed for each coil. This procedure ensures that seeds are in close proximity to the sensitivity 
peaks.

Next, we employ a separate region-growing phase correction 
on each coil with the previously identified seeds to remove the 
slowly varying phase components (Fig. 2b). We initiate the phase 
correction in each coil on a high-signal fat voxel. As a result, fat 
voxels in corrected coil images will tend to cumulate around 0 
radians (positive real part), whereas water voxels will cumulate around \( \pi \)-radians (negative real part).15 This seed-selection pro-
cedure thereby accounts for intercoil phase offsets, avoiding global
fat–water swaps across separate coils. However, correction accuracy can still degrade in regions away from the coil center where reduced coil sensitivity yields low image magnitude and noisy phase. Therefore, we propose to obtain accurate phase estimates by pooling information across coils. Here we assume that the coil elements in the phased array collectively provide sensitive coverage across the entire imaging field of view (FOV). The following linear combination of coil images can then be computed:

$$S_{\text{comb}}(r) = \sum_{i=1}^{N} S_i^\rho(r) \cdot |C_i(r)| / \sum_{i=1}^{N} |C_i(r)|$$

where $S_i^\rho$ denotes the phase-corrected image from the $i^{th}$ coil, and $N$ is the number of coils. Note that the coil-sensitivity profiles estimated from central $k$-space data contain residual image phase. To prevent intercoil inconsistencies due to this remnant phase, the phase-corrected coil images in Eq. 2 are weighted by the magnitude of coil sensitivities. Finally, the phase of $S_{\text{comb}}$ is used to classify each voxel as water or fat.

**Alternative PS-SSFP Reconstructions**

To compare the performance of the proposed multiseed combined-coil method, we implemented three alternative PS-SSFP reconstructions:

1. Single-seed individual-coil reconstruction (PS$_{ss}$): In PS$_{ss}$, a fat voxel centrally located within the volume was selected manually as a common seed for all coils. Phase correction was performed individually on each coil image starting with this common seed. Following phase correction, global phase offsets among
coil images were removed, and individual-coil water images were reconstructed. The final reconstruction was calculated as a weighted combination of individual-coil water images, where each coil’s weight was proportional to the magnitude of its sensitivity, as in Eq. 2.

2. Multiseed individual-coil reconstruction (PSms): In PSms, the starting seeds were determined according to the unsupervised selection procedure employed in the proposed method. The remaining parts of PSms were identical to the PSss reconstruction. Thus, water images were reconstructed separately for each coil and then linearly combined.

3. Single-seed combined-coil reconstruction (PScc): The first step of PScc was to calculate a linear combination of coil images:

\[
S_{\text{cc}}(r) = \sum_{i=1}^{N} S_i(r) \cdot C_i^*(r) \sum_{i=1}^{N} |C_i(r)|
\]

where uncorrected coil images \(S_i\) are multiplied with the complex conjugate of the coil sensitivities \(C_i^*\). Note that weighting uncorrected coil images by the sensitivity magnitudes as in Eq. 2 would cause signal loss due to intercoil phase inconsistencies. Instead, the combination in Eq. 3 removes from individual-coil images the low-spatial-frequency phase variations captured by the sensitivity estimates (including global phase terms). To account for gradual phase variations still remaining in the combination, region-growing phase correction was performed on \(S_{\text{cc}}\) using a central fat-voxel seed, and the resulting phase-corrected image was used for fat–water separation.

Experiments
Noncontrast-enhanced bSSFP angiograms were acquired at three separate stations in the lower extremities: the thigh, the calf, and the foot. Data were collected on a 1.5T GE (Milwaukee, WI) Signa scanner (40 mT/m maximum strength, 150/T/m.s maximum slew rate) using an 8-channel receive-only phased-array coil. Three volunteers were recruited for the study (two females ages 28 and 34, one male age 28), and all subjects gave written informed consent. The experimental protocols were approved by the local Institutional Review Board.

To generate angiographic contrast, we used a magnetization-prepared, segmented 3DFT bSSFP sequence that we developed in a recent study. Dual-acquisition bSSFP data were acquired and complex summed to mitigate banding artifacts due to field inhomogeneity. The following parameters were prescribed: superior–inferior readout direction, 90° flip angle, 5 msec TR (the minimum TR allowed by the readout requirements), 2.5 msec TE, 1.7 seconds inversion recovery time, 80 msec T2-preparation time, 1200 enodes/segment, 12-tip start-up catalyzation based on a Kaiser-Bessel windowed ramp, and 3 seconds recovery time. A relatively high flip angle was prescribed to increase suppression of muscle signal due to on-resonant magnetization transfer effects. In the thigh, an FOV of \(350 \times 350 \times 180\) mm³ was covered with 1.4 mm isotropic resolution in 7 minutes 25 seconds. In the calf, an FOV of \(310 \times 240 \times 140\) mm³ was covered with 1 mm isotropic resolution in 7 minutes 46 seconds. In the foot, an FOV of
was covered with 1 mm isotropic resolution in a total scan time of 6 minutes 28 seconds. All PS-SSFP reconstructions were performed using a block of size $6 \times 6 \times 6$ voxels. Prior to maximum-intensity projections (MIPs), all datasets were transformed to $k$-space, zero-padded to double the $k$-space coverage, and inverse Fourier-transformed. This procedure was performed to minimize partial volume effects and to improve visualization quality.22

As a reference for PS-SSFP reconstructions, IDEAL (Iterative Decomposition of Water and Fat with Echo Asymmetry and Least-Squares Estimation) fat–water separation was implemented on dual-acquisition bSSFP data separately collected using a multiecho bipolar-readout 3DFT sequence.23 The IDEAL sequence was implemented using TR = 10 msec and three echoes with 2.8-msec spacing, TE = (1.3, 4.1, 6.9) msec. To maintain identical spatial resolution, FOV, and scan time to PS-SSFP acquisitions at each station, IDEAL acquisitions were 1.5-fold accelerated and undersampled data were reconstructed using ARC (Autocalibrating Reconstruction for Cartesian Sampling).24 A multipeak IDEAL reconstruction was then performed to separate fat and water signals.25

Two complementary analyses were performed to evaluate PS-SSFP reconstructions. First, PS-SSFP water images were compared with unseparated bSSFP images. PS-SSFP classifies each voxel as either water or fat. It has been reported in the lower extremities at 1.5T that the average intensity of fat signals is at least twice as high as the average intensity of water signals.20 Thus, the intensity

![FIGURE 3: Dual-acquisition bSSFP images in the lower extremities, the foot (a) and the lower leg (b), collected using an 8-channel phased-array coil. Unseparated complex-sum images are shown for bSSFP, whereas water images are shown for PSms (multiseed, individual coil) and the proposed method. Note that PSms was performed individually on each coil, and seed selection was identical across the two methods (starting seeds marked with blue crosses). In both a and b, the top row shows magnitude images and the middle row shows phase images (see colorbar) obtained from an individual coil. Meanwhile, the bottom row shows the final image combined across coils. Relatively large variations are observed in phase images away from the sensitivity peak of the coils: in posterior regions of the foot image and superior–anterior regions of the lower leg (marked with dashed ellipses). While these variations cause fat–water misclassification in individual-coil and combined PSms images (marked with arrows), the proposed method produces more reliable phase estimates to improve tissue classification.](image-url)
of PS-SSFP water images should become smaller with improved fat suppression. To compare the level of fat suppression across different PS-SSFP methods, we measured the mean image intensity across axial cross-sections of each reconstruction. In each cross-section we calculated the ratio of the mean intensities measured in PS-SSFP versus bSSFP images (RbSSFP; expected to decrease with improved fat suppression).

It is possible that misclassification of water tissue that yield higher bSSFP signals than fat (e.g., synovial fluid) can introduce a downward bias in the intensity ratio of PS-SSFP to unseparated bSSFP images. To ensure that these ratio measurements are not significantly biased by suboptimal water signals, a separate control analysis was performed. In this analysis, PS-SSFP and IDEAL water images were compared after intensity normalization. For normalization, an identical region-of-interest (ROI) with homogeneous muscle signal (minimum size of 500 voxels) was selected across all reconstructed volumes. The mean signal intensity within the muscle ROI was normalized to unity separately for PS-SSFP and IDEAL images. PS-SSFP images with more reliable fat–water separation should yield similar intensities to the reference IDEAL images. In each axial cross-section, we calculated the ratio of the mean intensities measured in PS-SSFP versus IDEAL images (RIDEAL; expected to approach 1 with improved water signals). All statistical comparisons were performed using Wilcoxon signed-rank tests (P < 0.005).

Results
Balanced SSFP images of the foot and the lower leg from a sample coil, and corresponding water images reconstructed via PSms (multiseed, individual-coil) and the proposed method, are displayed in Fig. 3. The phase images become progressively noisier away from the sensitivity peak for each coil. Increased phase noise in turn causes local failures...
during phase correction, and regional fat–water misclassification in PS_{ms}. Note that residual fat signals in individual-coil images are prominent even after image combination across coils. In contrast, the proposed method achieves visibly improved fat suppression compared to PS_{ms}.

Representative bSSFP images of the thigh and the lower leg reconstructed via PS_{ss} (single-seed, individual-coil), PS_{ms}, and PS_{cc} (combined-coil) are shown in Figs. 4 and 5. Both cross-sectional and MIP views of water images—combined across 8 channels of the phased-array coil—show broad regions of fat–water misclassification in PS_{ss}, PS_{ms}, and PS_{cc}. The combination across coils prior to phase correction in PS_{cc} and the coil-wise seed selection in PS_{ms} partly improve water depiction compared to regular PS_{ss}. Nonetheless, water images obtained via the proposed method demonstrate enhanced tissue separation compared to PS_{cc} and PS_{ms}.

Quantitative assessments of the level of fat suppression ($R_{bSSFP}$) and the optimality of water signals ($R_{IDEAL}$) are listed in Table 1. Our proposed method yielded significantly smaller $R_{bSSFP}$ than each of the three alternative PS-SSFP reconstructions in the thigh, in the lower leg, and in the foot ($P < 0.005$), indicating that it achieves improved fat suppression. Furthermore, the proposed method attains the most similar image intensities to IDEAL (Fig. 6) among all PS-SSFP reconstructions in all body regions ($P < 0.005$). These results indicate that the proposed method achieves significantly more reliable fat–water separation compared to regular PS-SSFP reconstructions.

**Discussion**

PS-SSFP fat–water separation employs a correction algorithm to remove phase variations due to undesirable factors including coil sensitivity. This correction proves challenging in phased-array acquisitions since individual-coil image phase typically shows substantial variations away from the coil centers. The proposed method first uses a coil-wise seed selection for individual-coil phase correction and obtains accurate phase estimates near coil-sensitivity peaks. Phase-corrected images are then linearly combined to improve phase estimates in the remaining regions, thereby obtaining enhanced phase estimates across the imaging volume.

A number of effective techniques have been previously proposed for tissue separation in bSSFP imaging. Sequences that employ saturation or spectral-spatial pulses for fat suppression can reduce sensitivity to partial volume effects and

TABLE 1. Quantitative Assessments of Fat-Water Separation

<table>
<thead>
<tr>
<th></th>
<th>PSss</th>
<th>PSns</th>
<th>PScc</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>0.363 ± 0.033</td>
<td>0.242 ± 0.044</td>
<td>0.252 ± 0.042</td>
<td>0.181 ± 0.039a</td>
</tr>
<tr>
<td>RbSSFP</td>
<td>0.290 ± 0.053</td>
<td>0.269 ± 0.072</td>
<td>0.267 ± 0.088</td>
<td>0.246 ± 0.089a</td>
</tr>
<tr>
<td>Foot</td>
<td>0.176 ± 0.046</td>
<td>0.174 ± 0.049</td>
<td>0.176 ± 0.051</td>
<td>0.167 ± 0.048a</td>
</tr>
<tr>
<td>Thigh</td>
<td>2.163 ± 0.555</td>
<td>1.346 ± 0.184</td>
<td>1.485 ± 0.449</td>
<td>1.052 ± 0.213a</td>
</tr>
<tr>
<td>RIDEAL</td>
<td>1.766 ± 0.493</td>
<td>1.586 ± 0.377</td>
<td>1.623 ± 0.747</td>
<td>1.416 ± 0.403a</td>
</tr>
<tr>
<td>Foot</td>
<td>1.685 ± 0.724</td>
<td>1.725 ± 0.782</td>
<td>1.729 ± 0.748</td>
<td>1.670 ± 0.796a</td>
</tr>
</tbody>
</table>

Measurements are reported as mean ± SD across cross-sections.

*aSignificantly different results ($P < 0.005$).
chemical-shift artifacts. Yet because these pulses reduce scan efficiency and increase sensitivity to field inhomogeneity, they are often not preferred in imaging extremities. Meanwhile, Dixon-type methods including IDEAL use multiecho measurements to offer accurate quantification of subvoxel fat–water composition and improved immunity against field inhomogeneity. However, these methods require significantly prolonged scan times and complex reconstruction procedures. In contrast, PS-SSFP does not use special pulses, multiple echoes, or other sequence modifications. It separates fat and water based on a relatively simple phase-sensitive reconstruction, at the expense of increased sensitivity to partial volume effects. Therefore, the proposed method can offer fat–water separation with high scan and processing efficiency.

The application of PS-SSFP on phased-array acquisitions has been considered in several recent studies. One approach is to first form a linear-combination image across coils, and then to perform fat–water separation on the combination. This approach, related to PS$_{cc}$, can suffer from residual phase errors in the combined image due to inconsistencies of uncorrected image phase across individual coils. Alternatively, fat–water separation can be performed on individual-coil images as in PS$_{sa}$ and PS$_{ms}$. Images are then combined after correcting for global phase offsets among separate coils. However complex, intercoil phase inconsistencies may exist even after coil-wise phase correction. The proposed method comprises several technical advances to achieve improved fat–water separation compared to previous approaches. Unlike PS$_{cc}$, our method performs phase correction prior to image combination across coils. In this process, it utilizes an automated selection to place seeds in regions of high coil sensitivity as opposed to a common seed for all coils. Finally, unlike PS$_{sa}$ or PS$_{ms}$, it separates fat–water voxels based on an improved phase estimate obtained via combination of corrected coil images.

A basic limitation of PS-SSFP concerns the selection of the sequence TR. A TR of 4.6 msec at 1.5T (or 2.3 msec at 3T) ideally places fat and water resonances at the centers of adjacent passbands. While out-of-phase combinations can be acquired at odd multiples of the ideal TR (eg, TR = 6.9 msec at 3T), these longer TRs may be undesirable since they increase field-inhomogeneity induced phase variations. However, TR = 6.9 msec or longer could be required for 3T imaging where the ideal TR is too restricted to maintain practical readout resolutions. Therefore, PS-SSFP at higher field strengths can offer improved signal-to-noise ratio (SNR) while increasing sensitivity to field inhomogeneity. It is also possible to prescribe moderately longer/shorter TRs than the ideal value (eg, TR = 5 msec at 1.5T was the minimum possible TR in this study). Such alterations cause the fat resonance to be offset from the passband center, slightly perturbing the fat–water phase difference in dual-acquisition bSSFP. Because PS-SSFP assumes a $\pi$-radians fat–water phase difference, accurate tissue classification is expected when the total phase accrual due to chemical shift and field inhomogeneity is less than $\pi/2$-radians. Thus, TR perturbations that increase chemical-shift induced phase effectively reduce the tolerable range of field inhomogeneity.

The proposed method has some other technical limitations that are common to PS-SSFP reconstructions. First, the current implementation comprises two sequential phase-cycled acquisitions, increasing susceptibility to motion. To mitigate artifacts due to patient motion, retrospective motion correction can be performed using navigators incorporated into bSSFP sequences. Second, PS-SSFP classifies each voxel as either fat or water, introducing sensitivity to partial volume effects. Spatial resolution can be increased to reduce this sensitivity, while undersampling can be used to maintain scan-time efficiency. Lastly, when field inhomogeneity is significant, residual banding artifacts might be visible in dual-acquisition bSSFP images. To improve robustness against field inhomogeneity, the proposed method can be applied to complex-sum images from a greater number of phase-cycled acquisitions without any modification.

Several technical developments can be further considered to improve the proposed fat–water separation. While PS-SSFP assumes a single-peak model for the fat resonance, a multipeak extension could offer enhanced tissue delineation. Note that a multipeak model based on single-echo acquisitions would be underconstrained. However, a dual-echo acquisition may enable subvoxel tissue decomposition, assuming that the parameters of the fat spectrum are calibrated a priori. Another improvement concerns the phase correction step of the proposed method. We preferred a region-growing algorithm in this study because it yielded high-quality reconstructions in the lower extremities, and it offered computationally efficient reconstructions for three-dimensional datasets. However, iterative phase-correction algorithms based on graph cuts can further improve reliability against large field inhomogeneities.

The proposed fat–water separation method was demonstrated successfully for noncontrast-enhanced angiograms acquired in three body parts in the lower extremities. Although a relatively small number of healthy subjects is reported, these promising results motivate a more direct examination of the reliability of our method under clinical settings. In particular, future studies are warranted that consider a larger population, including patients with vascular disease, various other body parts and habitus, reproducibility assessments, and validation.

In conclusion, we have demonstrated improved phase-sensitive reconstructions of phased-array images, by combining an unsupervised seed-selection procedure for region-growing phase correction and an optimal pooling of phase information across coils. Thus, the proposed method is a promising technique for rapid fat–water separation in bSSFP applications.
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Conflict of Interest

The authors declare no conflicts of interest.

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