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Single-point Dixon water-fat imaging using 64-channel single-echo acquisition MRI

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Abstract

This paper presents a method for high-speed water-fat imaging using Single-Echo Acquisition (SEA) with an array of 64 localized coil elements and single-point Dixon sequence. The method forms two-dimensional separate water and fat images from a single echo data. Specifically, a channel correlation and region-growing algorithm was developed to extract the phase information from the single echo data, eliminating the need for multiple data acquisition normally required for water/fat separation. Phantom studies on a 4.7 T scanner show that the method can handle large inter-channel and cross-channel phase variations, even at relative high data noise levels. Assume that the water and fat are spatially separated and they can be identified by the phase discontinuity caused by the chemical frequency shift, the new method can acquire separate water and fat images without reducing the high frame rates of the SEA imaging method. Although its capability is limited if there are large susceptibility artifacts, disconnected tissues, or pixels with mixed fat and water signals, the new method is potentially useful for dynamic imaging of small animals, where the SEA imaging can provide high imaging speed but may suffer from reduced contrast due to the strong fat signals at short repetition time.

Keywords

Parallel Imaging; Water-Fat Imaging; Single-Echo Acquisition; Phase-Sensitive Reconstruction; Single-Point Dixon

INTRODUCTION

Single-Echo Acquisition (SEA) has been used to acquire 2D images with 256×64 pixels with a single echo that is simultaneously collected using an array of highly localized, 64-ch coil elements (1). As a result, extremely high frame-rates up to one frame per TR have been demonstrated (2). The high imaging speed of SEA appeals to several potential applications in small animal imaging where SEA can provide sufficient penetration depth and the conventional MRI is prone to ghosting artifacts coming from the peristaltic movement of internal organs and rapid cardiac/breathing motion of animals. For example, the normal

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heartbeat rate of adult mice can be as high as 680 beats per minute, and their breathing rate is up to 200 times per minute, several times faster than that of the human being (3). Although gating techniques can be used to reduce artifacts due to periodic motions, the high speed of SEA imaging is very valuable for capturing the rapid non-periodic kinetics while minimizing the motion artifacts.

However, at high frame rates, SEA imaging may suffer from reduced contrast due to the strong T₁ weighting. For example, fats have short T₁ and the strong fat signals limit the image contrast of the interested water protons. In dynamic contrast-agent enhanced T₁-weighted imaging, strong fat signals can often reduce the dynamic range of the tissue signals originated from contrast kinetics. Conventionally, fat-suppression or water/fat imaging are used to improve tissue contrast by suppressing undesirable fat signals (4,5). However, these methods typically require longer RF pulses or multiple acquisitions (e.g., CHESS (CHEMical Shift Selective saturation), STIR (Short Tau Inversion Recovery), or multi-point Dixon imaging methods (6–14)) therefore reduce the high frame rates of the SEA imaging methods.

In this paper, a single-point Dixon acquisition scheme was integrated with SEA imaging to acquire separate water/fat images. A critical component of this method is to estimate the chemical-shift induced phase information for water/fat separation. For this purpose, phase variations among the 64 channels in SEA must be appropriately accounted. Such phase variations may come from various sources such as the coils, cable/receiver delays, field inhomogeneity, and susceptibility effects, and can be time-varying due to system instability. Unfortunately, straightforward phase correction algorithm using calibration scan is not effective in dealing with these phase variations. To address this problem, a retrospective signal processing method based on channel signal correlation and region growing algorithm was developed. The method assumes that the water and fat are spatially separated and they can be identified by the phase discontinuity caused by the chemical frequency shift.

The proposed method was validated on a 64-channel prototype SEA imaging system using phantom studies. The results indicate that the new method can successfully remove channel-by-channel phase variations and other non-chemical shift induced phase variations. Given that water and fat are spatially separated, clearly separated 2-D water-dominant and fat-dominant images can be acquired with a single echo (i.e. without requiring additional calibration scans for phase calculation) for structures with smooth phase variations. Improved image contrast was obtained after water-fat separation, without sacrificing the high frame rate of the SEA imaging.

METHODS

Single-Point Dixon SEA Pulse Sequence

Figure 1 illustrates the sequence diagram used in the proposed method and the relative phase displacement of “Water” and “Fat” signals at three corresponding timing points in the rotating reference frame. In the sequence, the read-out data acquisition window is intentionally shifted to produce a relative phase difference between water and fat signals that will be used later for their separation (15–19). In single-point Dixon, two equations are

needed to decompose water and fat signals, and 0° (i.e. in-phase) or 180° (i.e. opposite phase) phase difference will result in a degenerate case (16, 19). In our experiment, T_{shift} is carefully designed so that phase difference between water and fat signals will be approximately 90° . This selection of orthogonal phase is optimal for separation of water and fat signals without noise amplification (15–18). In addition, the acquisition window is shifted to an earlier time to shorten the total acquisition time. The signal echo acquired is frequency-encoded using a linear readout gradient. For ultra-high imaging speed, only one echo from each channel is acquired. Therefore the spatial localization along the “phase-encoding” direction is determined by localized coil sensitivity (1). The echo is acquired with a certain phase-encoding gradient to compensate for the phase ramp due to the inherent wavelength effect of small coil size, as described in (2, 20). The single echo from each of the 64 channels will be individually Fourier transformed, stacked, and processed to form the desirable water/fat images.

Water and Fat Separation in SEA

Given that the coil-sensitivity is very localized along the y -direction, the frequency encoded echo signal from the c -th channel acquired using the sequence as described above can be approximated by

$$D_c(k_x) \approx \int [W(x, y_c) + e^{j\phi} F(x, y_c)] |S_c(x, y_c)| e^{j\theta_c(x, y_c)} e^{-jk_x x} dx \quad [1]$$

where k_x is the spatial frequency induced by the frequency encoding gradient, $W(x, y)$ and $F(x, y)$ are water and fat signals, respectively, y_c is the central location of the c -th coil along the y -direction, ϕ is the chemical-shift induced phase by the shifted acquisition window, $S_c(x, y)$ is the coil sensitivity, and $\theta_c(x, y)$ is the channel-dependant phase variations introduced by non-chemical-shift effects such as B_0 field inhomogeneity, tissue susceptibility, eddy currents, and complex coil sensitivity. In this work, ϕ is set to be 90° so that after the non-chemical shift phase error is estimated and removed, water/fat can be easily separated as the real and imaginary parts of the complex pixels in the reconstructed image. When a non- 90° phase shift is used, the water and fat components can be still separated. However, noise will be amplified as ϕ deviates from 90° .

The first step in the image reconstruction is a 1-D inverse Fourier transform of $D_c(k_x)$ in Eq. [1], which produces a line image from each channel:

$$\hat{I}_c(x) \approx [\hat{W}_c(x) + e^{j\phi} \hat{F}_c(x)] e^{j\theta_c(x)} \quad [2]$$

where $\hat{W}_c(x) = W(x, y_c) \cdot |S_c(x, y_c)|$ and $\hat{F}_c(x) = F(x, y_c) \cdot |S_c(x, y_c)|$, i.e., sensitivity-weighted water and fat signals, respectively. Then, a complex 2-D SEA image can be reconstructed by stacking all 64 image lines $\hat{I}_c(x)$, $c=1, 2, \dots, 64$, together. In the absence of the coil-dependent phase error, $\theta_c(x)$ in Eq. [2], the water and fat signals can be resolved straightforwardly by matching the real and imaginary parts on both sides of the equation

$$\begin{aligned}\text{RE}\{\hat{I}_c(x)\} &\approx \hat{W}_c(x) + \hat{F}_c(x) \cos \phi \\ \text{IM}\{\hat{I}_c(x)\} &\approx \hat{F}_c(x) \sin \phi\end{aligned}\quad [3]$$

From the above equation, it is easy to see that the choice of $\phi = 90^\circ$ is optimal because numerical solutions to Eq. [3] do not involve matrix inversion and potential noise amplification.

In practice, $\theta_c(x)$ can vary significantly from channel to channel and from location to location, therefore it needs to be estimated and corrected in order to resolve the water and fat signals. A simple method is to acquire a separate additional calibration scan with a sequence similar to the one shown in Figure 1, but without the readout window shift. In this case, $\theta_c(x)$ can be simply extracted from the complex calibration image (with $\phi = 0^\circ$). If necessary, multiple calibration scans can be performed periodically during the dynamic imaging to capture time-variant phase information, but doing so will reduce the high frame-rate of the SEA imaging. In addition, motions, flows, and system phase instability can lead to significant changes in the calibration term. A more efficient phase correction method is to use a 2-D region-growing algorithm based on a smoothness phase distribution assumption (21,22). However, because each channel has different phase factors, the 2-D phase map is not a smooth field and estimating it using a 2-D region-growing algorithm is difficult.

In the following, a phase correction algorithm using channel correlation and automatic 1-D region-growing is described in details. The new algorithm consists of three steps: (1) individual channel phase correction; (2) intermediate water and fat separation; and (3) channel combination based on correlations between intermediate water/fat image lines. The three steps are illustrated in Figure 2.

Step 1: Individual Channel Phase Correction—In general, if the image pixels would have arbitrary water/fat mixture ratio, it is not possible to distinguish $\theta_c(x)$ from the phase term in $\hat{W}_c(x) + e^{j\theta_c(x)} \hat{F}_c(x)$ just from the single echo data. In this paper, it assumes that water and fat pixels are spatially separated, which allows identifying and correcting $\theta_c(x)$ from the single echo data. The phase correction of each channel is performed using a 1-D region-growing algorithm. The phase correction is based on an assumption that the phase term, $\theta_c(x)$, is a spatially smooth function within the single image line from the c -th channel. This smooth component can be differentiated from the phase change due to water/fat chemical shift. In each channel, an initial seed pixel is chosen from the complex SEA image line and a 1-D region-growing algorithm starts from this pixel. To improve the robustness, the initial pixel is always chosen from points with high SNR and minimal phase difference with its neighboring pixels. The region-growing is based on the phase continuity between a phase vector and a new pixel to be considered. The phase vector is computed as the complex sum of all phase-corrected pixels in the vicinity of the new pixel, i.e., within a window of 9 pixels. Specifically, if the angular difference between a new pixel and the phase vector is over than 45° (an experimentally determined threshold for 90° water/fat phase difference), it is determined to have a water/fat phase jump and a 90° phase-correction is applied to the

new pixel being processed. Otherwise, the region will simply grow to the new pixel without correction. As shown in the earlier work, using a neighborhood of pixels as a baseline for region-growing has several advantages over the region-growing methods based on pixel pairs (23). First, the noise effect on the phase vector can be minimized, as the random Gaussian noise can be suppressed by complex sum. Secondly, the method can largely prevent the accidental phase correction error from a noisy pixel to propagate during the region-growing process, therefore limits the error to an isolated pixel rather than the whole image region otherwise.

The region growing process provides the estimated phase error term, $\hat{\theta}_c(x)$, then the phase correction can be simply performed for each channel by removing the phase term from the original image, i.e., $I'(x) = \hat{I}(x) \cdot e^{-j\hat{\theta}_c(x)}$.

Step 2: Intermediate Water and Fat Separation—After the initial phase correction, an intermediate water and fat separation is performed. Assuming that region-growing algorithm starts from a water-dominant pixel, Eq. [2] leads to

$$I'_c(x) \approx \hat{W}_c(x) + j\hat{F}_c(x) \quad [4]$$

for $I' \in \mathbb{C}$. Then, intermediate “water” and “fat” portion of the image line can be decomposed as $\hat{W}_c(x) = \text{Re}\{\hat{I}'\}$ and $\hat{F}_c(x) = \text{Im}\{\hat{I}'\}$. However, if a fat-dominant pixel was chosen as the initial pixel, the phase correction will introduce an additional $\pi/2$ phase term and

$$I'(x) = \hat{I}(x) e^{-j[\hat{\theta}(x) + \frac{\pi}{2}]} = (\hat{W}_c(x) + j\hat{F}_c(x)) e^{-j\frac{\pi}{2}} \quad [5]$$

Therefore, the solutions become $\hat{W}_c(x) = -\text{Im}\{\hat{I}'\}$ and $\hat{F}_c(x) = \text{Re}\{\hat{I}'\}$. Figure 2 (step 2) shows the effect of the initial pixel selection in the “Water” and “Fat” separation. Note that due to the channel phase variation, the initial pixel could be “water” and “fat” rather randomly from channel to channel. This ambiguity will be resolved next using correlation between channel signals.

Step 3: Channel Combination Using Correlations—To form consistent 2-D water and fat images, it is necessary to identify if the selected initial pixel for each channel in Step 2 was water-dominant, or fat-dominant. This is achieved using the correlation between intermediate water/fat line images acquired in the previous step across adjacent channels. Specifically, assuming that physical water and fat parts have spatial continuity from channel to channel, then two water signals from adjacent channels should have stronger spatial correlation than that of a water signal and a fat signal. Note that this correlation comes from the physical continuity of the underlying objects or tissues. Therefore the correlation exists

regardless of the coil sensitivity overlap. To effectively use this constraint, we define a parameter called sum of point-by-point multiplication index (SPMI):

$$SPMI_{WW}(y_c, y_{c+1}) = \sum_{x=1}^{N_x} |\hat{W}_c(x, y_c)| \cdot |\hat{W}_{c+1}(x, y_{c+1})|$$

$$SPMI_{WF}(y_c, y_{c+1}) = \sum_{x=1}^{N_x} |\hat{W}_c(x, y_c)| \cdot |\hat{F}_{c+1}(x, y_{c+1})|$$
[6]

where $\hat{W}$ and $\hat{F}$ are intermediate “Water” and “Fat” lines that might have been mislabeled. The combination process starts by selecting an arbitrary beginning channel. Then, based on SPMI, water and fat images in the adjacent channels are determined, as illustrated in Figure 3. Specifically, if $SPMI_{WW} < SPMI_{WF}$ the “water” and “fat” image lines of the next channel are swapped. Assuming that there is no complete signal nulling in any of the channel image lines, this process can be propagated to all channels to form a consistent 2-D “water” image and a “fat” image. Note that, in T_1 -weighted SEA images, usually the fat image will have higher intensity than water image. This fact can be used to determine which image should be assigned as the fat-only image. Specifically, for each image, a binary mask is created using an intensity threshold, which equals to three times of the standard deviation of the noise pixels (i.e. pixels in the background). Then, the image with higher average intensity (of all pixels in its own mask) is assigned as the fat-only image. Alternatively, the relative leading or lagging phase relationship along the boundary between the “water” region and the “fat” region can be used for the water/fat image identification as shown in (19). This is because the fat has a slightly higher resonance frequency and the phase difference between water and fat signals at the echo time can be derived accordingly.. We have found that both methods can provide reliable water/fat identification for the SEA images in our experiments.

Experiment

To test the proposed methodology, a cylindrical phantom as illustrated in Figure 4 was constructed using a 12 cm diameter plastic box with seven compartments filled with different materials: (1) vegetable oil fat ($T_1 = 250$ ms at 4.7 T), (2) distilled water ($T_1 = 4250$ ms at 4.7 T), and (3) water doped with 1g/L CuSO_4 ($T_1 = 780$ ms at 4.7 T) (24). Single-point Dixon SEA images were acquired on a 4.7 T/33 cm Bruker Scanner with a 64-channel linear array (with 2 mm by 8.1 cm planar-pair elements) using the proposed sequence. Scan parameters were: TR = 100 ms, TE = 20 ms, RBW = 50 kHz, ST = 3 mm, $N_x = 256$, and FOV = 14 cm. For the spin-echo sequence shown in the Figure 1, the acquisition window was shifted by $T_{\text{shift}} = 357$ us from the in-phase echo time to create the orthogonal 90° phase difference between water and fat signals at 4.7 T (3.5 ppm chemical shift water/fat). A 256×256 fully encoded in-phase image was scanned using a regular spin-echo protocol with the same scan parameters, but with 256 phase encodings to show the structures. Then, another dataset with a shifted acquisition window (with the same T_{shift}) was acquired. For SEA reconstructions, the phase-encoding line with overall phase ramp compensation effect was taken from the fully encoded dataset as the single echo to be used. The proposed algorithm and water and fat combination using SPMI were implemented in Matlab

(MathWorks, Natick, MA) and were used to reconstruct from SEA data. The processing procedure was fully automated without any operator intervention.

To evaluate the effective image-contrast from water/fat separation, we define a factor called normalized contrast by dynamic-image range (NCDR)

$$NCDR = \frac{\left| \sum_{(x,y) \in ROI_1} I(x,y)/N_{ROI_1} - \sum_{(x,y) \in ROI_2} I(x,y)/N_{ROI_2} \right|}{I_{\max} - I_{\min}} \quad [7]$$

where $I_{\max}$ and $I_{\min}$ are the maximum and the minimum signal intensities in the whole image respectively, and N_{ROI1} and N_{ROI2} are number of pixels in two ROIs, respectively. Conventional image-contrast evaluating method such as measuring signal ratio or absolute signal difference between tissues is not useful for our application, because absolute image intensity level does not change before and after water and fat separation.

RESULTS

Figure 4 (b) shows a high-resolution sum-of-squares (SOS) magnitude image from the 256×256 in-phase data. Only the central $12 \text{ cm} \times 8 \text{ cm}$ portion of ROI is displayed in the SOS image for better visualization. Figure 5 (a) and (b) show the SEA magnitude image and phase image (after taking the cosine value), respectively. Note the low contrast between the two water compartments due to strong fat signals in Figure 5 (a). In addition, due to the channel difference, the phase image in Figure 5 (b) appears rather random. Figure 5 (c) shows the phase error-map corresponding to Figure 5 (b) after 1-D region-growing. Although there were partial volume effects in the image, the algorithm was able to successfully identify, within each channel, the 90° phase jumps. However, the phase between adjacent channels was not all consistent. Figure 5 (d) shows the phase map after phase between adjacent channels were corrected using SPMI. The phase error was removed from the original SEA image, leaving only 0° and 90° phase values (corresponding to water and fat, respectively).

Figure 6 shows the effect of phase correction on image separation and image contrasts. The intermediate “water/fat” images after 1-D phase correction are shown in Figure 6 (a) and (b), respectively. The incorrectly assigned “water” and “fat” lines are due to selecting “fat” pixels as initial pixels in some channels. After correlation based channel combination, the final water/fat reconstruction is shown in Figure 6 (c) and (d), respectively. Comparing the water/fat images with the phantom configuration in Figure 4, it shows that the proposed algorithm correctly produces water- and fat-only partitions. Note that, as compared with Figure 5 (a), the signal contrast between the water compartments has been significantly enhanced due to the removal of fat signals. To quantitatively evaluate the image contrast, selected regions of interest as illustrated in Figure 6 (c) and (e) were used. In this experiment, water/fat separation improved image contrast between the water compartments by 2.4 times according to NCDR specified in Eq. [7].

To evaluate the robustness of the proposed line-by-line phase correction algorithm, zero-mean complex Gaussian random noise with different variance were added to the acquired signal in the image domain. The water/fat maps produced from the corresponding SEA images were compared with reference water and fat maps (as shown later in Figure 8 (a) and (b)). Figure 7 shows the percent of the number of water/fat pixel changes within ROI plotted as a function of the added noise level. The standard deviation of the noise, σ , was computed from a 10 by 30 pixel region in the background area. Interestingly, in a large range of added noise levels (σ to 4σ), the identified water/fat pixels essentially had no change, indicating that the proposed method is robust against the additive noise. Only when the relative noise level continued to rise ($> 4\sigma$), the significant change in water/fat decomposition occurred. The change rate appeared to be linear. For example, with a relative noise level of 7σ , the percent of water/fat pixel change was still below 11%.

In addition, ground-truth water and fat maps were manually selected from the fully-encoded 256×256 reference image, as illustrated in Figure 8 (a) and (b). Then, SEA water-only and fat-only maps (shown in Figure 8 (c) and (d)) were compared with the reference to evaluate errors. The difference between the top and middle rows are shown in Figure 8 (e) and (f). As shown, the error happens mainly on the boundaries of the compartments. The errors in Figure 8 (e) are dominantly localized to the signal-void area, i.e., the plastic separators between compartments. Therefore, they have little or no impact on the actual water-only image. The large errors on the bottom left of Figure 8 (f) may come from the low signal due to the coil sensitivity in the area. In both images, note that most error pixels on the boundary are due to the low-resolution of the SEA reconstruction. These errors will be significantly reduced as the spatial resolution of the SEA imaging is expected to be improved by on-going technical developments.

DISCUSSION AND CONCLUSIONS

There are several potential issues associated with the proposed phase correction algorithm in the proposed method. First, it requires that the non-chemical-shift induced phase is spatially smooth within a channel. This condition is generally satisfied for typical spin-echo SEA imaging, or well-shimmed gradient-echo SEA imaging. But caution should be used when dealing with areas with large susceptibility effects, because the phase variations can be very rapid. Second, there are possibly degenerate cases, such as two adjacent channels cover purely fat and purely water tissues respectively, which can make it difficult to use channel correlation to resolve water and fat ambiguity. However, this is rarely the case for realistic biological tissues under the normal experimental conditions. The other issue for the phase correction algorithm is that tissues in FOV may not be connected. The signal void of the underlying channels may prevent successful use of channel correlation over the gap areas (22). In some cases, this issue may be alleviated by padding physical structures such as a water tube between two isolated ROI regions, as a usual solution. Another limitation of the phase correction algorithm is that it assumes that any pixel in the image is dominated by either water or fat and there are detectable phase discontinuity at the water/fat region interface. The algorithm identifies pixels as either water or fat from the single echo data. We expect that this assumption is reasonable for muscle imaging where water and fat are spatially separated. If this assumption is not valid or water/fat must be decomposed in each

pixel, then a more sophisticated phase correction algorithm is necessary for phase correction (25), or the multiple-point Dixon or spectral-encoding methods can be used to decompose water and fat components at the cost of longer acquisition time and lower temporal resolution (11–12,21–22). Alternatively, it can alternate the of the in-phase and out-phase data required by Dixon methods in successive single echo acquisitions. Decomposed water and fat images can then be reconstructed for each echo.

We presented a method for high-speed water-fat imaging using Single-Echo Acquisition (SEA) with an array of 64 localized coil elements and single-point Dixon sequence. Specifically, a channel correlation and region-growing algorithm was developed to extract the phase information from the single echo data to reconstruct water/fat images. Phantom studies on a 4.7 T scanner showed that the method can handle large inter-channel and cross-channel phase variations, even at relative high data noise levels.

Single-echo acquisition imaging using 64-channel array coil has been used to achieve extremely high frame rate (e.g. 200 frames/second). With such a high frame rate, the TR is very short and image contrast will become an important factor of consideration in imaging method design. Under the assumption that water and fat are spatially separated, the new method can acquire separate water and fat images, without reducing the high frame rates of the SEA imaging method. Therefore, it is expected to be valuable for potential dynamic MR imaging applications such as small animal imaging, where the SEA imaging can provide high imaging speed but may suffer from reduced contrast due to the strong fat signals at short repetition time.

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Figure 1.

Spin-echo based single-point Dixon SEA pulse sequence, and corresponding relative displacement of "Water" and "Fat" spins on the rotating reference frame (t_a) before applying 90° RF pulse, (t_b) after applying 90° RF pulse, and (t_c) at the shifted echo-time. A single echo will be used to form 2-D water/fat images. The use of 90° phase shift between water and fat signals allows them to be mapped to the real and imaginary parts of a complex pixel. This makes it possible to separate the water and fat components with minimal noise amplification.

Figure 2.

Illustration of the proposed water and fat separation method for SEA imaging: (Step 1) channel-by-channel phase correction by 1-D region-growing; (Step 2) intermediate |*water*| and |*fat*| separation; and (Step 3) channel combination based on correlation between intermediate water/fat images.

Figure 3.

Channel combination based on correlation between intermediate 'water' and 'fat' images. The graph shows how the 21st and 22nd channels are combined. In the example, water/fat images defined in the 22nd channel were swapped according to a correlation factor, SPMI defined in Eq. (6).

Figure 4. Illustration of the phantom used in the experiment. (Left) partitioned space filled with different materials: vegetable oil fat ($T_1 = 250$ ms), water doped with 1g/L CuSO_4 ($T_1 = 780$ ms), and distilled water ($T_1 = 4,250$ ms) at 4.7 T. (Right) the 256 $\times$ 256 phantom image with conventional spin-echo sequence.

Figure 5. SEA image and the phase correction effects: (a) SEA magnitude image; (b) SEA phase image (shown after taken cosine). Note the channel-to-channel phase variations and the 90° phase jump between water and fat compartments; (c) The corresponding phase image after 1-D region-growing. Note that the 90° jumps were removed; (d) Chemical-shift induced phase image (0° and 90°) extracted after the phase correction.

Figure 6.

Intermediate $|*dlquote*|water|*drquote*|$ and $|*dlquote*|fat|*drquote*|$ images before and after channel combination: (a) $|*dlquote*|water|*drquote*|$ image and (b) $|*dlquote*|fat|*drquote*|$ image before channel combination; (c) water-only image and (d) fat-only image after processing; (e), SEA image collected with a single conventional (non-shifted) spin-echo. The stripes in (a–b) were corrected by the combination process. Note the significant contrast improvement in (c) as compared with (e).

Figure 7. Variations of the water/fat pixel numbers (normalized by the total number of water and fat pixels in the references) as a function of additive zero-mean Gaussian noise. The graph shows that the algorithm is robust against additive noise in a large range.

Figure 8.

Water/fat masks and separation accuracy: (a) water mask manually extracted from 256 | *times*| 256 high-resolution reference based on phantom configuration; (b) the corresponding fat mask; (c) and (d) water and fat masks from the proposed method; (e) and (f) error maps between (a) and (c), and (b) and (d), respectively. Note that most errors are located on the trivial areas (plastic separators) or tissue boundary due to the low resolution of the SEA image.