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RESOLVING ESTIMATION UNCERTAINTIES OF CHEMICAL SHIFT ENCODED FAT-WATER IMAGING USING MAGNETIZATION TRANSFER EFFECT

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Abstract

Purpose: B0 field inhomogeneity may cause significant errors in chemical shift encoding (CSE)-based fat-water (F/W) separation. We describe a new approach to improve its robustness using novel B0 field map pre-estimation.

Methods: Our method exploits insensitivity of fat to magnetization transfer (MT) effect, which allows generating fat-insensitive B0 field priors with full or partial spatial support using a low-resolution MT-weighted scan. The full prior can be employed by most F/W separation methods for initialization or data demodulation. We also propose a modified region-growing algorithm, in which the partial prior is utilized for its initial seeding.

Results: The MT-based B0 priors significantly reduced F/W errors of three representative F/W separation methods in all cases. In cases with moderate B0 inhomogeneity, the full prior allowed error-free separation even with basic, voxel-independent processing. When coupled with methods exploiting B0 field smoothness, it significantly improved separation accuracy even in presence of strong inhomogeneities. Seeding the region-growing with the partial prior significantly improved performance of F/W separation including cases with spatially disconnected tissues.

Conclusions: MT-based B0 field pre-estimation provides valuable prior information for F/W separation, which may significantly improve its robustness at the expense of nominal (<5–10%) scan time increase.

Keywords

Magnetization Transfer; Chemical Shift Imaging; Dixon Fat-Water Separation; IDEAL

INTRODUCTION

Since its introduction by Dixon (1), chemical shift encoding (CSE)-based fat-water (F/W) imaging has evolved into a methodology of choice for pathology visualization unobscured by bright fat signal and for tissue fat quantification (2). In this approach, fat and water

components are first encoded into MRI signal by varying acquisition echo time and then separated using model-based mathematical inversion. The model-based isolation of fat signal improves efficiency and signal-to-noise ratio compared to the standard fat suppression using inversion recovery (3) and frequency selective (4) methods, respectively. Further, decomposing MRI signal into fat and water components rather than suppressing the former enables estimation of fat fraction for quantitative assessment of adipose tissue (5–7). More recently, modeling F/W components jointly with the main (B_0) field inhomogeneity (8), T_2^* decay (9), and multi-peak fat spectra (10,11) created new opportunities for assessment of fatty liver disease (12) and tissue iron overload (13).

CSE-based F/W imaging must deal with estimation uncertainty due to the existence of several solutions to the inverse problem owing to two independent sources of signal off-resonance (i.e., the fat chemical shift and the B_0 field inhomogeneity). This ambiguity may lead to significant errors such as incorrect assignment of separated signals to the F/W components (i.e., fat/water swapping) or a subtler leakage of fat and water signals into the opposite channels. Over the years, the lack of universal solution stimulated a continuing interest to the problem (14–24). A common strategy to tackle the separation ambiguity is to engage *prior* knowledge about the B_0 field such as its spatial smoothness. Several joint estimation approaches explicitly enforce the smoothness by penalizing solutions that exhibit rapid spatial B_0 field variations (15,16). The region-growing methods implicitly utilize the smoothness to propagate trusted B_0 values from reference (seed) locations (14,23). However, the region-growing can be affected by low accuracy of initial B_0 field values in the seed. Further, the region-growing can be unstable, especially in spatially disjoint anatomies. Relying on the B_0 smoothness alone does not guarantee robust F/W separation as the assumption is oftentimes challenged by the B_0 field perturbations due to significant magnetic susceptibility differences, e.g., at tissue-air interfaces. Their effect on the B_0 field is orientation-dependent and is more pronounced in non-axial planes, especially when the interfaces are transverse to the main magnetic field (25).

Another approach to improve F/W separation is to utilize a sufficiently accurate B_0 field estimate to facilitate convergence to the correct solution (24,26). However, measuring B_0 field map is a non-trivial problem as direct estimation of B_0 field from multi-echo images is similarly confounded by fat (27). In this paper, we describe a novel method to generate B_0 field priors for the use with CSE-based F/W separation algorithms that circumvent this problem with the help of magnetization transfer (MT) effect (28). Our method capitalizes on existence of MT between water and tissue macromolecules, and on absence of MT between fat and either water or tissue macromolecules (29). We demonstrate that this phenomenon creates an opportunity to generate B_0 field map estimates without fat interference that are sufficiently accurate to facilitate resolution of F/W separation uncertainties in a variety of imaging scenarios. Our method is intended to improve performance of the existing CSE-based F/W separation algorithms rather than to be used instead of them. In this paper, we demonstrate the utility of the new approach with several representative F/W separation methods in their original and modified forms applied to multiple gradient echo data.

THEORY

We consider a general tissue model that consists of macromolecular, water, and fat protons (29). The model can describe voxels that contain either tissue or fat or their mix on both microscopical (e.g., in the presence of fatty cells in liver) and macroscopical (partial voluming of pure tissue and fat) levels. The macromolecular and water protons exchange magnetization, but the fat protons do not interact with them due to the absence of efficient mechanisms to transfer magnetization from fat to either water or tissue macromolecular protons (29). When MT preparation is applied far from resonance (>2.5 kHz (30)), it saturates magnetization of the macromolecular protons and indirectly affects water signal through MT, while leaving the fat signal unaffected. This heterogeneous response makes MT a marker of the tissue water (Fig. 1); the effect was previously utilized to visualize fat-free tissue water signal (31). Here, we propose to capitalize on this phenomenon for an unambiguous, fat-free estimation of the B0 field priors as described next.

Without loss of generality, we consider a spoiled multiple gradient echo sequence that can be run with and without MT preparation. As MT attenuation can be attributed to water protons only, the image (s_n) acquired at n^{th} echo time (t_n) can be written as a linear combination of fat (ρ_F) and MT-attenuated water (ρ_W) signal components modulated by the transverse relaxation rate R_2^* and the B0 field ψ :

$$s_n(\alpha, TR, \eta) = \left(\eta \rho_W(\alpha, TR) + \rho_F(\alpha, TR) \sum_{m=1}^M \beta_m e^{i2\pi f_m t_n} \right) e^{-R_2^* t_n} e^{i2\pi \psi t_n} \quad [1]$$

Here, f_m is a resonant frequency of the m^{th} fat peak ($m=1, \dots, M$) relative to water, and β_m is a relative amplitude of the m^{th} peak ($\sum_{m=1}^M \beta_m = 1$). The signal explicitly depends on pulse sequence parameters such as repetition time TR and excitation flip angle α , and on a saturation factor η , which accounts for water signal attenuation due to MT preparation. Let us assume that s_n^{OFF} and s_n^{ON} are acquired without ($\eta^{\text{OFF}} = 1$) and with ($\eta^{\text{ON}} < 1$) MT saturation, respectively, while the other pulse sequence parameters affecting MR signal (i.e., TR and α) are kept the same for both acquisitions. Under these conditions, the difference between s_n^{OFF} and s_n^{ON} can be attributed to MT effect only, and their complex-valued difference isolates the water component:

$$s_n^{\text{MT}} = s_n^{\text{OFF}} - s_n^{\text{ON}} = (1 - \eta^{\text{ON}}) \rho_W e^{-R_2^* t_n} e^{i2\pi \psi t_n}, \quad [2]$$

The fat-free MT attenuation maps s_n^{MT} can be processed further to approximate the B0 field map by taking the image phase difference at arbitrary echo times t_k and t_l (32),

$$\phi_{kl} = \angle [s_k^{\text{MT}} \text{conj}(s_l^{\text{MT}})] \quad [3]$$

and calculating the field map as follows:

$$\psi_{\text{MT}} = \frac{\phi_{kl}}{2\pi(t_k - t_l)} \quad [4]$$

Here, $\angle$ denotes the operation of extracting image phase. The B0 field map ψ_{MT} is not affected by fat chemical shift and can be applied to improve performance of F/W separation as exemplified in the next sections.

METHODS

Figure 2 presents a general outline of the method, which consists of six steps (**S1-S6**). First, multi-echo (ME) images are acquired at full resolution (**S1**), and additional MT-weighted (MTw) ME calibration images are collected at lower resolution (**S2**) by sampling only few central k -space lines. Next, the ME images are downsampled to the resolution of the MTw-ME images by selecting data on the same central k -space lines (**S3**). Then, the images are subtracted according to Eq. [2] to yield complex-valued MT attenuation maps (**S4**). On the subsequent step (**S5**), the MT maps are supplied to a field map estimation algorithm, which begins with calculation of the inter-echo phase difference (Eq. [3]), followed by its unwrapping and transformation to ψ_{MT} (Eq. [4]). To this end, the algorithm yields the field map with partial spatial support (i.e., it is fully defined in MT-attenuated tissues). On the step **S6**, depending on F/W separation algorithm used, the partial B0 field map can be employed directly, or interpolated to generate a prior with full spatial support using the regular B0 smoothness assumption. Next, we describe two methods to apply the B0 field prior with representative F/W separation algorithms.

Estimation of Full B0 Field Map Prior

To estimate a full B0 field prior ($\tilde{\psi}$) from the partial one (ψ_{MT}), we engage the assumption about its smoothness to approximate the B0 values in tissues without MT effect (i.e., pure fat) via interpolation/extrapolation (33). For a proof of concept, we adapt the weighted moving window polynomial fit method, which was originally proposed in parallel MRI for coil sensitivity processing (34). Specifically, for each voxel location $\bar{r}_0 = [x_0, y_0]$, we perform a weighted least squares fit of the 2D quadratic polynomial function,

$$P(\bar{\beta}; \Delta\bar{r}) = \beta_5 \Delta x^2 + \beta_4 \Delta y^2 + \beta_3 \Delta x \Delta y + \beta_2 \Delta x + \beta_1 \Delta y + \beta_0, \quad [5]$$

to the partial field map ψ_{MT} for all $\bar{r} = \bar{r}_0 + \Delta\bar{r}$ within the radius $r_{\text{max}} (|\Delta\bar{r}| < r_{\text{max}})$. In detail, the coefficient vector $\bar{\beta} = [\beta_0, \dots, \beta_5]$ is found for the given location $\bar{r}_0$ as

$$\bar{\beta}(\bar{r}_0) = \underset{\bar{\beta}}{\operatorname{argmin}} \sum_{|\Delta\bar{r}| < r_{\text{max}}} \left\| s_1^{\text{MT}}(\bar{r}_0 + \Delta\bar{r}) \cdot [\psi_{\text{MT}}(\bar{r}_0 + \Delta\bar{r}) - P(\bar{\beta}; \Delta\bar{r})] \right\|_2^2 \quad [6]$$

Then, we calculate the B0 value as the value of the polynomial function in the central voxel $\bar{r}_0$,

$$\tilde{\psi}(\bar{r}_0) = P(\bar{\beta}(\bar{r}_0); 0) = \beta_0 \quad [7]$$

The fit in Eq. [6] is weighted by the magnitude of the MT attenuation map with the highest signal, s_1^{MT} , which emphasizes contributions from locations with more trusted B0 values (i.e., voxels with more significant MT effect) and downplays contributions of B0 values from locations with less pronounced MT effect. Repeating the procedure for all voxels yields the full B0 field map prior $\tilde{\psi}$. The processing code for the weighted local polynomial fit in Eq. [6] is available online at https://www.medphysics.wisc.edu/~samsonov/local_polyfit.m. On the Step 6 of the pipeline (Fig. 2), the prior can be applied to demodulate the data to make them conform to zero-valued initialization adopted in most F/W separation algorithms or can be used as an initial guess itself.

Generation of Seed Areas for Region-Growing F/W Separation

Apart from being a source for estimation of the full B0 field prior, the partial prior can be used with some algorithms directly. In this section, we propose a modified region-growing (RG) method that utilizes the partial MT-based B0 prior for a robust seeding of the region-growing.

Like the original RG method (14), the F/W separation begins at seed areas, in which the B0 prior is assumed to be sufficiently close to the underlying B0 field. The region-growing proceeds from voxel to voxel, each time initializing F/W separation in a new voxel by a B0 value extrapolated from neighboring processed voxels. The original RG method finds the seeding area heuristically by statistical analysis of a low-resolution B0 field map obtained by **I**terative **D**ecomposition of water and fat with **E**cho **A**symmetry and **L**east-squares (IDEAL) method (8,35). As the B0 field map from IDEAL is still affected by fat, it does not guarantee proper initialization of the region-growing. In the proposed MT-based RG (MT-RG) (Fig. 3), we select the seed areas from the MT-based B0 prior, which is not affected by fat. The areas are identified as regions where the B0 values are most accurate and precise, i.e. as locations with most significant MT attenuation. To identify the trusted regions, the echo-time average of magnitude MT attenuation maps (obtained in Step 4 in Fig. 2) is first thresholded using the automatic method of Otsu (36) to yield an MT mask. The object voxels that are most likely to suffer from partial voluming with background are eliminated by eroding the mask. The remaining objects in the binary mask are labeled using automatic identification of

connected components (37). The B0 field prior is then estimated in each of the labeled components from the phases of MT attenuation maps (Eq. [2]) according to Eqs. [3][4]. We note here that the scheme may create multiple seed areas with extended spatial support as opposed to the single low-resolution seeding area found by the standard method (14). In our case, the region-growing starts simultaneously from all seeding areas and continues until all voxels are processed.

Data Acquisition

Informed consent was obtained from all volunteers according to the Institutional Review Board policy. The data were collected on a 3.0T GE MR750 (Waukesha, WI) using two different acquisition protocols. In the first protocol, we used a 3D multiple spoiled gradient echo pulse sequence with optional MT preparation, which was run to obtain ME data for F/W separation (*main* ME data) and additional MT-weighted data for B0 pre-estimation (*calibration* MTw-ME data). As our method requires equal TRs of the main ME and calibration MTw acquisitions, MT preparation in the calibration sequence automatically adds the dead time to the main ME sequence. To avoid the scan time increase, we also tested an optimized (short-TR) scheme, in which the number of echoes in calibration MTw sequence was reduced to a minimum of two to compensate for the MT pulse duration. Such optimization allows avoiding the TR increase while still permitting B0 mapping from the remaining echoes. Table 1 summarizes acquisition parameters for all test datasets. Calibration MTw-ME data in datasets #1–2 were acquired with the same resolution as the main ME data to allow for retrospective optimization of resolution of the MTw data. MTw-ME data in the remaining datasets (#3–5) were acquired with 5–10% resolution of the main ME dataset, which was found to be sufficient for stable performance of the algorithms. Dataset #4 was acquired with manually offset shim values to simulate B0 shimming failure.

Data Processing

All processing was performed in Matlab Release 2015b (The MathWorks, Inc., Natick, Massachusetts, USA) on per slice basis (i.e., in 2D). For datasets #1, 2 (Table 1), sixteen central k -space lines were extracted from the fully sampled MTw-ME data to simulate low-resolution acquisition; the experiments with the other datasets (#3–5) used actual low-resolution MTw-ME data. The field maps were estimated from the first and the second echoes as specified by Eqs. [3],[4] using the 2D phase unwrapping (available at <https://goo.gl/v9LoZX>). Parameter $r_{\max}$ in Eq. [6] and the radius of erosion window in the partial B0 field estimation (Fig. 3) were 11 and 3 pixels, respectively. We also calculated the B0 field map directly from low-resolution ME images (i.e., without subtraction of MTw-ME data). F/W separations were performed on coil-combined images (38) and utilized a multi-peak fat spectral model (11). The fit ignored R2* effects due to the small number of echoes in the data and the short echo times used.

We evaluated the utility of the full and partial B0 field priors in two sets of experiments. The full prior was evaluated with three representative F/W separation methods with different algorithmic and computational complexity. They included basic IDEAL that processes voxels independently of each other (35), original RG method (14), and graph-cut method (17). IDEAL and RG were implemented in-house and graph-cut method was obtained from

Fat/Water Toolbox (18). The full prior was applied to demodulate the ME images according to the signal model (Eq. [1]) by multiplying the n^{th} image by $e^{-i2\pi\tilde{\psi}t_n}$ to compensate for the B0-induced phase. Both original and demodulated data were supplied to the algorithms for evaluation of the zero-valued and proposed priors, respectively. In the second set of experiments, we studied performance of the standard RG and proposed MT-RG algorithms, the former utilizing standard heuristics (14) and the latter relying on the partial field map for seed area selection. As there is no ground truth F/W separation for in vivo data, we adapted the accuracy quantification approach used in 2012 ISMRM Challenge on Fat/Water Reconstruction (<http://challenge.ismrm.org/node/17>). For each reconstruction case, all results were first visually assessed to identify the reconstruction method that yields result without visible F/W errors, which was then used as a surrogate ground truth. Then, the binary mask of voxels affected by F/W errors was created by first taking absolute difference between water components from a given method and the ground truth, and then automatically thresholding the result using Otsu's method (36) to minimize contributions of background noise. The error was calculated as the number of voxels in the binary mask divided by the total number of voxels in the object mask and converted to percent units.

RESULTS

Figure 4 compares performances of the zero-valued and proposed full MT-based (Fig. 4a) B0 field priors with IDEAL and RG algorithms (dataset #1 in Table 1). (No results for graph-cut algorithm are shown as it performed accurately with both priors, likely due to moderate B0 inhomogeneity). No visible errors in both methods were detected when using data demodulated by our MT-based prior, with difference detected only in 0.09% of voxels. The similarity of separation results indicates that MT-based field map prior may enable robust F/W separation even with the basic IDEAL separation. Applying the algorithms to data without demodulation (i.e., assuming the zero-valued prior) results in visible errors affecting 4.3% and 1.2% of voxels for IDEAL and RG methods, respectively. Figure 5 shows the separation results with the direct B0 field map (i.e., without MT subtraction) for the same data. The use of the direct prior does not resolve F/W swaps and increases the errors to 10.1% and 5.7% for IDEAL and RG, respectively, which supports that improvement of F/W separation observed for the new prior is due to the absence of fat signal in the MT difference images.

Figure 6 shows results of evaluation of the full prior in the presence of strong field inhomogeneity (dataset #2 in Table 1). When applied to non-demodulated data, all algorithms produce visible separation errors, with graph-cut method suffering the least (21.8, 33.3, and 8.0 % error for IDEAL, RG, and graph-cut, respectively). Applying IDEAL to data demodulated by the proposed prior reduces the error ~5-fold (to 4.1%), although some residual errors remain. This implies that separating voxels independently (i.e., without engaging spatial correlations within the algorithm) may not be sufficient to avoid F/W errors even with the MT-based B0 field prior when B0 inhomogeneity is strong ($[-400...800]$ Hz for the case). At the same time, using the MT-based prior with methods that exploit the B0 field spatial correlations, i.e., RG and graph-cut methods, reduced the errors to 0.4% and 0% (no visible errors), respectively.

Figure 7 demonstrates an example when automatic heuristics of the standard RG algorithm leads to a suboptimal seed placement in a slice from the phantom object dataset (#3 in Table 1). The phantom object is composed of water, oil bottle, and two small vials (solid squares) with 10% gelatin representing a limited amount of MT-sensitive tissues (2% of total object area) (Fig. 7a). The seeding regions were identified automatically by the standard RG (dashed square in Fig. 7a) and by the proposed MT-RG methods (Figs. 7b,c). Initialization of the region-growing by standard seeding traps the estimation into a local minimum leaving the residual fat signal in the water channel (Fig. 7d). Region-growing with seeding based on the MT-based B0 field prior correctly places fat (oil bottle) and water (background water and gelatin) signals into the corresponding channels.

Figure 8 compares F/W separation with RG algorithms for anatomy with spatially disjoint tissues (dataset #4 in Table 1). The standard RG creates F/W errors in left thigh (8.1% of object voxels affected), which is spatially disconnected from tissues containing the seed (right thigh). At the same time, the MT-based prior seeds the region-growing with trusted B0 field values in both left and right thighs resulting in F/W separation without visible errors.

Figure 9 shows additional comparisons of the standard and MT-based RG methods in the head/chest dataset (#5 in Table 1) for slices with connected and disconnected tissues. In the connected tissue case (Fig. 9a), instability of the region-growing with standard seed selection creates sporadic F/W swaps throughout the image plane affecting 4.3% of object voxels. The error increases to 9.2% in the disconnected tissue case (Fig. 9b), an anatomical configuration that is more challenging for the standard RG (23). The partial MT-based field map in MT-RG stabilizes separation and produces no visible F/W errors in both cases.

DISCUSSION

B0 field pre-estimation is highly desired for robust CSE-based F/W imaging but can be confounded by off-resonance interference from fat. In our method, we first eliminate fat from the images using MT effect and then generate B0 field priors not affected by the chemical shifts of fat spectral peaks. The priors can reduce the estimation uncertainty and increase robustness of F/W separation by helping algorithms distinguish between phase evolutions of different origins (i.e., fat chemical shift and B0 field inhomogeneity). Therefore, the method may be particularly beneficial when pulse sequence design, imaging conditions, and/or anatomy of interest are suboptimal for the given F/W separation algorithm. One example is imaging at higher resolutions, which increases echo time spacing and makes it particularly difficult to perform F/W separation reliably (14,39). Other examples include F/W imaging in anatomical locations with spatially disjoint tissues (e.g., in lower/upper extremities) or in the presence of strong B0 field inhomogeneities (± 1000 Hz in Fig. 8). Using the proposed method for very strong B0 inhomogeneities (e.g., for near-metal imaging), however, may require adjustment of off-resonance frequency of the MT pulse towards higher values to avoid direct fat saturation.

MT effect is observed in most tissues including neural tissues, muscles, cartilage (40) and in other collagen-containing tissues such as in breast, liver, tendons (41–43). The wide-spread presence of MT effect allows generating the full priors using regular B0 field smoothness

assumption (Figs. 4, 6). Yet, it is possible to envisage imaging scenarios where a given slice may have insufficient amount of the tissues of interest for generation of the full B0 field map from the partial prior, for example, for boundary slices in the excitation slab that contain mostly fat (especially in obese subjects). In these cases, the accuracy of the full prior estimation is likely to benefit from extending our processing pipeline from 2D to 3D to engage the neighboring slices with MT-sensitive tissues. Alternatively, the partial prior can be used directly with select F/W algorithms such as region-growing, whose performance may depend critically on availability of even partial information about the B0 field (Figs. 7–9). As the region-growing method can benefit from both full and partial B0 priors, it is a prime candidate for combination with our method. Other potential ways to utilize the partial prior include combination with regularization-based F/W separation methods that solve for all voxels simultaneously by enforcing B0 field map smoothness (15,16). The combination may be possible through an additional regularization term that penalizes difference between the estimated B0 field and its prior in locations with non-zero MT effect. Further, even partial separation could be utilized to increase confidence of fat likelihood analysis in probabilistic F/W separation approach based on spectral complexity of fat (44).

The methods presented in the paper are related to several previously proposed techniques. The lack of MT effect in fat was utilized for fat-free visualization of tissue water (31). In our method, the phenomenon is utilized to improve separation of fat and water components, which can be used not only for visualization but also for quantitative analysis. Other methods also demodulate data using an approximate B0 field calculated mathematically from the assumed magnetic susceptibility variations in the volume without (26) or with (24) consideration of other sources of variations of the B0 field. However, such estimation can be performed only for 3D scans, depends on the ability to classify tissues, and assumes normative susceptibility values. Our method measures the B0 field experimentally and, as such, can deal with B0 field variations regardless of their origins.

Our method has several limitations. The MT scan may increase the scan time, except in scans that already acquire both ME and MTw-ME data (e.g., for fat-insensitive MT-weighted imaging in liver (42,45) and fat-corrected quantitative MT imaging of the human optic nerve (46)). The scan time increase in our experiments was in the range of 5–10%, which is acceptable in most situations. Importantly, the overhead can be reduced in parallel MRI protocols by using MTw-ME data for parallel MRI calibration as well. This optimization would obviate the need for acquisition of a fully sampled k -space center in the main ME dataset and, hence, reduce the overall overhead to ~2/4% for 4x/2x accelerations, respectively (assuming a calibration dataset of 8% resolution of the fully sampled data). Another potential source of the scan time increase is TR lengthening due to MT preparation in MTw-ME sequence. In our experiments, we avoided this overhead by reducing the number of echoes in in MTw-ME data. This optimization permitted three echoes in the main ME data and two echoes in MTw-ME data, which are minimum required for joint F/W/B0 estimation and for B0 pre-estimation, respectively. Thus, the possibility of adapting the proposed priors for dual-echo F/W imaging (47) without scan time penalty remains unclear. One potential way to eliminate the dedicated MT pulse in the dual-echo methods to minimize time penalty is to employ the on-resonance MT phenomenon, which allows

inducing MT effect by varying the duration of the excitation RF pulse (48). However, feasibility of these optimizations remains subject of future research.

CONCLUSION

We described a new approach to improve CSE-based F/W separation algorithms that capitalizes on the ability of MT effect to serve as an exclusive marker of tissue water signal. B0 field priors generated with the help of MT effect represent an independent source of prior information, which can significantly increase robustness of a wide variety of the algorithms at the expense of a small (less than 5–10%) scan time increase. The new methodology may noticeably improve performance of F/W imaging in suboptimal conditions, including imaging in the presence of significant B0 field inhomogeneity.

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Figure 1:
Subtraction of images without (OFF) and with (ON) MT saturation removes fat but preserves water signal in tissues attenuated by MT effect.

Figure 2:
General outline of the proposed methodology.

Figure 3:
Flowchart of the MT-based RG algorithm.

Figure 4: Performance of IDEAL and RG algorithms in the presence of moderate B0 inhomogeneities (#1 in Table 1). **a.** The MT-based B0 field prior. **b.** F/W separation results for zero-valued and the MT-based B0 field priors. Note F/W errors (arrows) when the algorithms are applied with the zero-valued prior.

Figure 5:

Performance of IDEAL and RG algorithms with a B0 field prior obtained directly from ME data without MT subtraction. **a.** The direct B0 field prior. **b.** F/W separation results. Note abundant F/W errors (arrows) for both algorithms.

Figure 6:

Algorithms' performance with the zero-valued and the full MT-based (a) B0 priors in the presence of strong B0 field inhomogeneities (#2 in Table 1). All algorithms fail with default zero-valued prior (top row in b; dashed arrows point to errors of graph-cut algorithm). The proposed prior improves performance of all algorithms (bottom row in b), leaving noticeable errors for IDEAL, very minor errors for RG, and eliminating errors for graph-cut method.

Figure 7:

Comparison of the region-growing algorithms in the phantom data (#3 in Table 1) **a:** Phantom layout. **b:** Low-resolution MT attenuation map (1st echo). **c:** Seed areas with the MT-based B0 field prior (squares indicate centers of gelatin vials). **d:** Separation results. The seed automatically selected by the standard RG algorithm (dashed square in **a**) results in poor initialization of region-growing and leads to residual fat signal in the water component. The proposed algorithm initialized by the partial MT-based prior from (c) correctly separates fat from water.

Figure 8:

Comparison of the region-growing methods in spatially disjoint tissues (#4 in Table 1). The dashed lines outline the seed areas chosen by the standard (RG) and proposed (MT-RG) algorithms from low-resolution IDEAL and MT-based B0 field maps, respectively. Note errors in the former case.

Figure 9: Performance of the region-growing algorithms in the head/chest dataset (#5 in Table 1) for two representative slices with connected (a) and disconnected (b) tissues. Standard RG suffers from errors, especially for the more challenging case of disconnected tissues. MT-RG demonstrates stable performance in both cases.

Table 1.

Summary of protocol parameters for test datasets used in the paper.

Dataset	Data Matrix (ME/MTw-ME)	TE ₁ / TE (ms)	ME/MTw- ME #Echoes	TR(ms)	MT pulse (shape/width/offset/angle)	Coil Type
1. Brain	192×192/192×192	1.57/1.72	8/3	23	Fermi/8ms/3kHz/600°	32-ch head array
2. Ankle	160×160/160×160	1.57/1.72	8/8	35	Fermi/10ms/2.5kHz/495°	8-ch foot/ankle array
3. Phantom	256×256/256×12	1.36/1.86	3/2	10.6	Sinc/1.7ms/3kHz/170°	8-ch NV array
4. Thighs	256×153/256×8	1.32/1.72	3/2	11.5	Fermi/1.8ms/3kHz/140°	8-ch torso array
5. Head/Chest	256×256/256×16	1.31/1.79	3/2	10.6	Sinc/1.7ms/3kHz/170°	8-ch NV array