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ARTICLE

Robust High Resolution Fat-Water Separation in the Abdomen during Free-Breathing by Self-Gated 2D Radial TrueFISP Imaging

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Abstract: Accurate high resolution fat-water separation in the abdomen is challenging due to respiratory motion. In this work, we propose a robust high resolution fat-water separation strategy in the abdomen during free breathing by employing radial sampling with a golden angle increment. To this end, a radial TrueFISP sequence was modified enabling the echo time TE to change from projection to projection, to force fat signals to behave in a conspicuous manner through time, so that they can be detected and separated from water signals through temporal processing. Thus, the center signal (DC) of each radial readout can then be used for respiratory gating, allowing the generation of multiple images at different TEs at multiple breathing states. Finally, any fat-water separation technique can be used to synthesize high resolution fat and water images at arbitrary breathing states. Good separation of fat and water signals was achieved using the radial TrueFISP sequence during free breathing without streaking artifacts or blurring due to respiratory motion.
Keywords: Fat-water separation; TrueFISP; Self-gating; Dynamic imaging; Free breathing.

Introduction

Invivo, Magnetic Resonance (MR) images usually contain both fat and water signals, which differ slightly in frequency, making it possible to generate images where these two types of tissues are separated [10]. In applications where fat tends to obscure the pathology, or where the disease itself has to do with adipose tissues, such ability can prove very valuable.

Fat water separation with free breathing is challenging due to motion artifacts. There are several methods to avoid the anatomy motion artifacts, such as breath holding, where this method requires patient cooperation, but is limited in use, because many patients have difficulty performing the necessary breath-holds [11, 12, 16]. Another method is respiratory self-gating [1-3], which uses the DC-signal in the central k-space. The DC-signal is induced by changes of spin density in the excited slice and formed by sampling the center of k-space repeatedly over time [4]. The self-gating technique is used with many applications like 2D and 3D Cartesian sequences [4-6] as well as radial ones [7, 8].

For abdominal imaging applications, several MRI techniques have been used for fat-water separation. These include the Dixon method [9.10], direct phase encoding (DPE) [11] and iterative decomposition of water and fat with echo asymmetry and least-square estimation (IDEAL) [12]. Respiratory motion can lead to image quality deterioration and inaccurate measurements, such as ghosting and blurring artifacts in the reconstructed data. While breath holding removes respiratory motion artifacts, at the same time it limits spatial resolution [13, 14]. Alternatively, free breathing abdominal imaging could be combined with the methods proposed to avoid respiratory motion artifacts, while continuing to provide a good temporal and

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spatial resolution. Therefore, established strategies for fat-water separation with free breathing are quite capable of separating fat and water signals, and require at least three images for the separation to be performed, making it difficult to achieve good temporal resolution in dynamic imaging [9-12]. In contrast, Ababneh *et al*. [16] succeeded in separating fat and water signals in dynamic MRI and provided improved temporal resolution by the combined three-point Dixon method for fat-water separation and Unaliasing by Fourier-encoding the overlaps using the temporal dimension (UNFOLD) [16, 17]. This method involves an assumption that fat signals are not very dynamic. Even when fat signals prove to be quite dynamic, suppressing their low temporal frequency content is expected to lead to significant overall suppression. The method provided a unique combination of imaging speed, high signal-to-noise ratio (SNR) and high contrast between myocardium and blood pool. In this work, fat-water separation method in [15] was combined with self-gating technique and used with free breathing in the abdomen. Therefore, a regular 2D radial TrueFISP sequence was modified to allow TE to vary from projection to the next. TE was adjusted here in a predetermined manner, to force fat signals to behave in a peculiar and readily recognizable fashion over time. Using temporal processing, the temporal variations imposed on fat signals can be recognized and fat signals can be separated from water signals.

Radial k-space trajectories became a part of this work, because they are suitable for dynamic imaging and have been used in many applications, such as cardiac imaging [18-21] and abdominal imaging [22, 23]. Radial MRI has a higher sampling density for the central k-space and higher spatial and temporal resolution and is insensitive to object motion during data acquisition [24, 25].

In the present work, we aimed to separate fat and water signals during free breathing abdominal imaging. Therefore, we integrated the fat-water separation method [15] with the self-gating technique while at the same time modifying the 2D radial TrueFISP sequence. Results were obtained *invivo* at 3T for the abdomen.

Materials and Methods

Healthy volunteers participated in the study following the guidelines of the local institutional review board, including written informed consent. This work uses the 2D radial TrueFISP sequence, characterized by a train of alternating excitation pulses (±α), separated by a constant time interval (repetition time TR). It starts with a number of dummy RF pulses to hasten the set-up of a steady state magnetization. The pulse sequences were modified to enable TE variations from one projection to the next, using the TE(t) pattern as in Fig. 1a. To achieve fat and water separation, the 2D radial TrueFISP pulse sequence was modified to make the echo time vary from one projection to the next as in Fig.1b for subsequent radial projections at constant TR [15]. A sequence of 4 TEs was periodically repeated following a radial golden angle projection order φ_{GR}=111.246°. Four images with different contrast were generated using DC gating technique for each data set. The coil channel providing the highest sensitivity towards respiratory motion was selected manually and gating windows were derived from the DC signal (Fig. 2). In this work, the width of the gating windows has been selected by choosing a constant number of projections. The signals within each gating window were used to generate images at different TEs using non-uniform fast Fourier transform (NUFFT) gridding [26]. In total, 2001 projections were acquired, where each window included 631 radial projections. Finally, the application of appropriate filters to the image series allows one to discriminate fat and water as described in Ref. [15]. The imaging parameters were: TR = 4.0 ms, (TE_1 = 1.6 ms, TE_2 = 2 ms, TE_3 = 2.4 ms), matrix size = 256 x 256, flip angle = 40°, FOV= 400x400 mm^2, slice thickness = 5 mm and resolution=1.56 x 1.56.

All data from self-gating scan was reconstructed offline using a MatLab software package (Math Works, Natick, MA). In this work, we integrate the fat-water separation method used in [15] with self-gating 2D radial technique during free breathing abdominal imaging. Results were obtained *invivo* at 3T for the abdomen.

In this study, the center signal (DC) of each radial readout used for respiratory gating allows the generation of multiple images at different TEs in multiple breathing states.

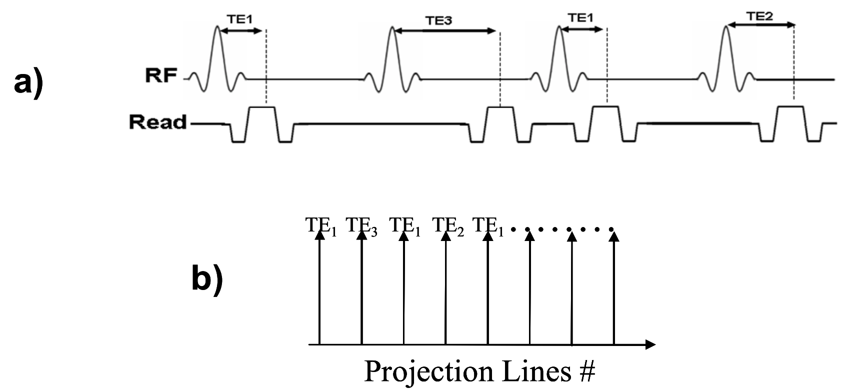

FIG. 1. a. The modified TrueFISP sequence. b. The acquired projections with different echo times are spaced by an angle increment of 111.246º.

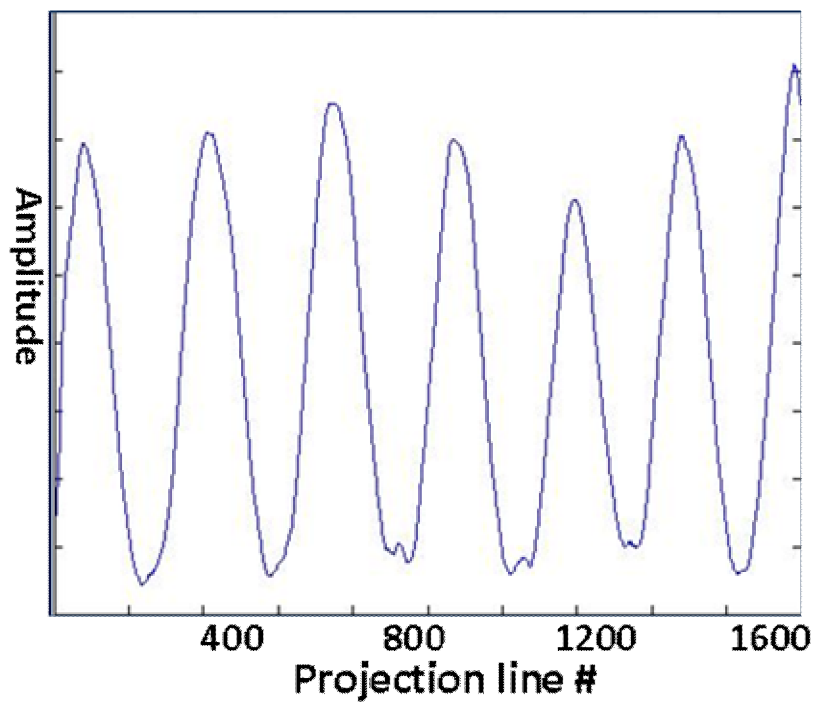

FIG. 2. The self-gating signal *vs*. the projection number from the coil channel number 15.

Results

Experiments were performed on a 3T system (Siemens, Erlangen, Germany) using a 32 spinal coil positioned about the mid portion of the body and body array. Fig. 2 shows the self-gating signal *vs*. the projection number from the coil channel number 15, which is selected manually, because it provides the highest sensitivity toward the respiratory motion. The two parallel lines indicate the chosen window for respiratory gating. Fig. 1 shows the modified sequence, where TE changes from projection to projection (Fig. 1b). As shown in Fig. 1a, TE (t) takes on the successive values of TEs, where TE1 = TE_o, TE2 = TE_o + ΔTE and TE3 = TE_o + 2ΔTE. TE_o is the shortest possible echo time allowed by the unmodified sequence and ΔTE is the echo time increment. The echo time increment ΔTE was kept extremely short in this work (~ 400 µs). In comparison, in the original description of the three-point Dixon method [10], ΔTE would be the value required for an 180^o offset between the fat and water signals. This choice of a short 400 µs ΔTE stems from the need to keep TE and TR short in a TrueFISP sequence.

Fig. 3 shows the calculated water and fat in a healthy volunteer acquired under free breathing conditions, the calculated water (a and b) and fat (c and d), where a and c images represent the inspiration state and b and d images represent the expiration state. Fig. 4 is for another volunteer, where Fig. 4a shows the water image and Fig. 4b shows the fat image. The water-only and fat-only images were obtained using the algorithm proposed in [15]. Banding artifacts, common with TrueFISP sequences, were observed. The white arrow indicates banding artifacts in Fig. 3a.

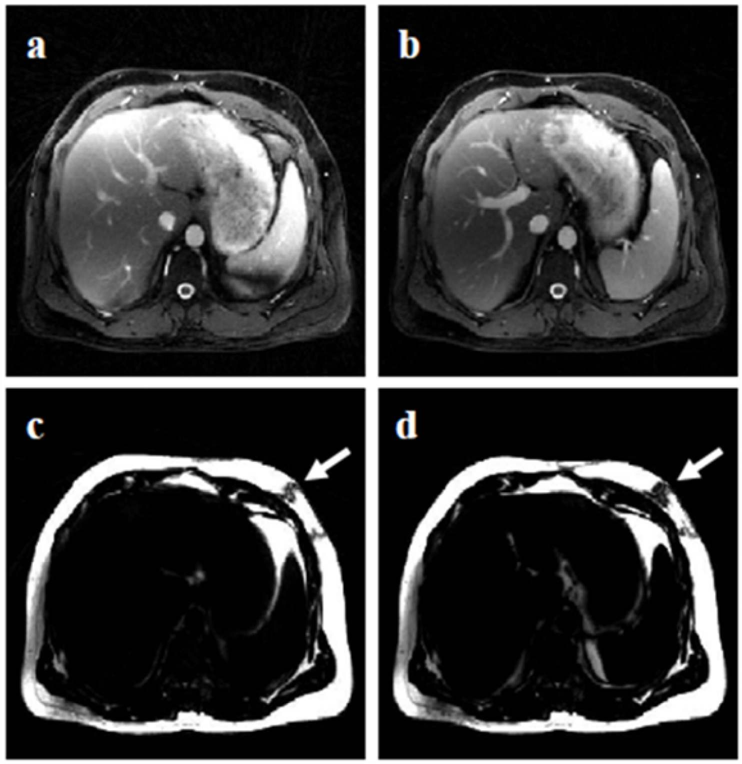

FIG. 3. One phase acquired at 3T in a healthy volunteer is shown here, (a) and (b). Water-only and fat-only results are shown in (c) and (d), respectively.

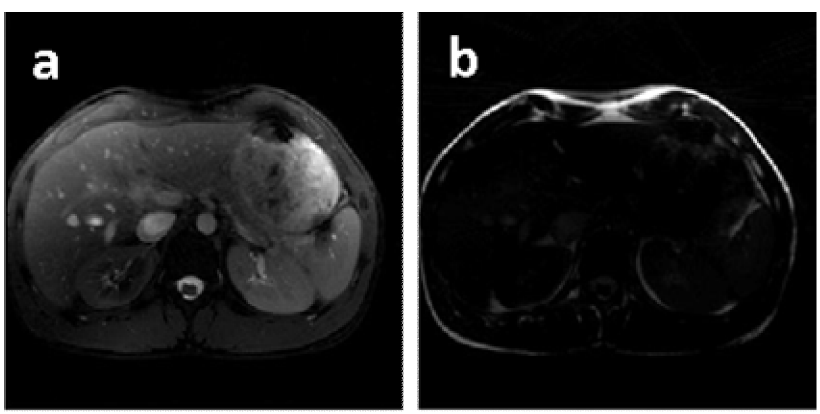

FIG. 4. One phase acquired at 3T for a different healthy volunteer is shown here. (a) Water-only, (b) fat-only.

Discussion

A novel approach to separate fat and water signals in the abdomen combined with self-gating radial TrueFISP is presented here. This approach provides good fat-water separation, reduces blurring artifacts caused by respiratory motion and enhances the image resolution. The self-gating method was successfully used to track respiratory motion. Therefore, fat-water separation is achieved in all breathing stages. Fig. 1 shows the accepted data for expiration and inspiration used for reconstruction, where 631 radial projections out of 2001 were used for each window. By comparing the DC-signal variations from all coils used in the scan, coil number 15 was selected manually, because it provided the highest sensitivity towards respiratory motion.

The selected number of projections for reconstruction takes into account the trade-off between better SNR and enhanced image resolution. Therefore, despite using a partial part of the acquired data (631 projections out of 2001), it was sufficient to achieve these goals.

The 2D radial TrueFISP sequence was modified by changing the echo time TE from projection to projection, to force fat signals to behave in a conspicuous manner through time, so that they can be detected and separated from water signals through temporal processing. The echo time increment ΔTE should be large enough to induce large phase differences between fat and water signals, yet small enough to avoid undue increases in TR in our TrueFISP sequence. A value of ΔTE = 400 μs was considered as an acceptable compromise between these two conflicting demands.

The present method is aimed at clinical applications, where good temporal resolution and good fat suppression are both crucial. While the concept has been demonstrated in 2D, future work will be targeted on extending the method to self-gated 3D radial imaging for robust fat-water separation in the abdomen. Further, the approach might prove to be particularly useful in contrast-enhanced breast imaging, where bright fat signals tend to obscure lesion-related water signals and where good temporal resolution is important to accurately capture dynamic signal enhancement.

The TrueFISP pulse sequence is sensitive to off-resonance effects, leading to banding artifacts. These artifacts result whenever off-resonance reaches a value equal to $\pm\frac{1}{2TR}$, which indicates the allowed range for banding-free imaging. The banding artifact shown in Fig. 3 was generated while using TR = 4.0 ms. The results of our study show that TrueFISP with radial acquisition during free-breathing is feasible for abdominal MRI studies and shows that even small variations in TE (0.4 ms) were sufficient to separate fat and water in dynamic objects.

Conclusion

This approach was tested in time resolved abdominal imaging. Good separation without streaking artifacts or blurring due to respiratory motion was obtained in all studied cases. The separation for free breathing was accomplished by incorporating the modified 2D radial TrueFISP sequence with self-gating technique. Self-gating reduces blurring artifacts caused by respiratory motion and enhances the image resolution.

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