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Ananth J. Madhuranthakam
GE Healthcare, UK

Huanzhou Yu
GE Healthcare, United States

Ann Shimakawa
GE Healthcare, United States

Reed F. Busse
GE Healthcare, United States

Martin P. Smith
Harvard Medical School

See next page for additional authors

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Authors

Ananth J. Madhuranthakam, Huanzhou Yu, Ann Shimakawa, Reed F. Busse, Martin P. Smith, Scott B. Reeder, Neil M. Rofsky, Jean H. Brittain, Charles A. Wallin, and Jennifer Yost

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Technical Note

T_2-Weighted 3D Fast Spin Echo Imaging With Water–Fat Separation in a Single Acquisition

Ananth J. Madhuranthakam, PhD,[1*] Huanzhou Yu, PhD,[2] Ann Shimakawa, MS,[2] Reed F. Busse, PhD,[3] Martin P. Smith, MD,[4] Scott B. Reeder,, MD, PhD,[5] Neil M. Rofsky, MD,[4] Jean H. Brittain, PhD,[3] and Charles A. McKenzie,, PhD[6]

Purpose: To develop a robust 3D fast spin echo (FSE) T_2-weighted imaging method with uniform water and fat separation in a single acquisition, amenable to high-quality multiplanar reformations.

Materials and Methods: The Iterative Decomposition of water and fat with Echo Asymmetry and Least squares estimation (IDEAL) method was integrated with modulated refocusing flip angle 3D-FSE. Echoes required for IDEAL processing were acquired by shifting the readout gradient with respect to the Carr-Purcell-Meiboom-Gill echo. To reduce the scan time, an alternative data acquisition using two gradient echoes per repetition was implemented. Using the latter approach, a total of four gradient echoes were acquired in two repetitions and used in the modified IDEAL reconstruction.

Results: 3D-FSE T_2-weighted images with uniform water–fat separation were successfully acquired in various anatomies including breast, abdomen, knee, and ankle in clinically feasible scan times, ranging from 5:30–8:30 minutes. Using water-only and fat-only images, in-phase and out-of-phase images were reconstructed.

Conclusion: 3D-FSE-IDEAL provides volumetric T_2-weighted images with uniform water and fat separation in a single acquisition. High-resolution images with multiple contrasts can be reformatted to any orientation from a single acquisition. This could potentially replace 2D-FSE acquisitions with and without fat suppression and in multiple planes, thus improving overall imaging efficiency.

Key Words: 3D FSE; 3D T2-weighted imaging; water-fat separation; IDEAL; fat suppression
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T_1-WEIGHTED (T_1W) and T_2-weighted (T_2W) images are staples of clinical magnetic resonance imaging (MRI) and are often acquired with and without fat suppression. A 3D acquisition allows contiguous thin slices with relatively high signal-to-noise ratio (SNR), which can be reformatted in multiple orientations from a single volumetric acquisition. While high-resolution 3D T_1W images can be acquired in feasible scan times (1), high-resolution 3D T_2W images historically required prohibitively long scan times (2). Hence, routine clinical T_2W imaging largely depends on 2D multislice acquisitions, usually in multiple planes (eg, sagittal, axial and/or coronal) to achieve high in-plane spatial resolution in multiple dimensions, with a consequence of increasing the total examination time.

T_2W images are commonly acquired using rapid acquisition with relaxation enhancement (RARE)(3)(also known as fast spin echo [FSE] or turbo spin echo [TSE])-based techniques. In an FSE sequence, multiple Carr-Purcell-Meiboom-Gill (CPMG) echoes are acquired per excitation pulse. However, the number of echoes that can be acquired before signal diminishes from T_2 decay is limited. This considerably increases the scan time for a high-resolution 3D imaging, by limiting the number of CPMG echoes that can be acquired per excitation pulse. A variety of improvements to prolong the effective rate of signal decay by modulating the refocusing flip angles (FAs) have been proposed (4–6). Utilizing these modulated refocusing FAs, very long echo trains have been previously developed that acquire high-resolution 3D images with clinically useful T_2W contrast in clinically acceptable scan times (7,8).

Another issue that increases total examination time is the frequent need to acquire one or more 2D orientations with and without fat suppression. Short tau inversion recovery (STIR) with FSE imaging is a commonly used fat suppression technique that provides

[1]Applied Science Lab, GE Healthcare, Boston, Massachusetts, USA.
[2]Applied Science Lab, GE Healthcare, Menlo Park, California, USA.
[3]Applied Science Lab, GE Healthcare, Madison, Wisconsin, USA.
[4]Department of Radiology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts, USA.
[5]Departments of Radiology, Medical Physics, Biomedical Engineering and Medicine, University of Wisconsin, Madison, Wisconsin, USA.
[6]Department of Medical Biophysics, University of Western Ontario, London, Ontario, Canada.
*Address reprint requests to: A.J.M., Ansin-241, Beth Israel Deaconess Medical Center, 330 Brookline Ave., Boston, MA 02215.
E-mail: Ananth.Madhuranthakam@ge.com
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uniform attenuation of fat signal (9), but suffers from reduced SNR and has mixed contrast with T_1-dependence. Conventional fat suppression methods using chemically selective suppression (CHESS)(10) can be applied to FSE; however, uniformity of fat saturation is susceptible to B_0 inhomogeneities, particularly in large field-of-view (FOV) and off-isocenter imaging. Other fat-suppression techniques include spectral-spatial pulses (11), but they are also sensitive to B_0 inhomogeneities. All of these fat suppression methods provide water-only signal, discarding all fat information, often necessitating the need for acquisitions with and without fat suppression to fully characterize fat-containing tissues.

Chemical shift-based methods exploit resonant frequency differences to separate the signal from water and fat into two different images (12). With FSE-based sequences, these techniques acquire multiple images with small relative shifts in the echo time with respect to the CPMG echo to measure the relative phase shifts between water and fat (13). Three-point methods have been shown to measure the B_0 inhomogeneities directly and demodulate them from the acquired source images, making these techniques robust to B_0 inhomogeneities (14,15). One of the main challenges with conventional water–fat separation methods is that postprocessing requires accurate phase unwrapping algorithms. Various methods have been developed to address this challenge (16–18). An alternative chemical shift-based water–fat separation method uses a least-squares approach, iterative decomposition of water and fat with echo asymmetry and least squares estimation (IDEAL)(19). Additionally, IDEAL uses asymmetric echo shifts to maximize the SNR performance of the water–fat decomposition for all combinations of water and fat within a voxel (20). IDEAL has been demonstrated to provide robust water–fat separation with 2D T_1W, T_2W, and 3D T_1W imaging sequences (21,22).

In this work we integrate the IDEAL chemical shift-based method with the modulated refocusing flip angle 3D-FSE to develop a method that can produce 3D T_2-weighted water and fat separated images robustly in a clinically feasible scan time. Various challenges of the integration of 3D-FSE with IDEAL are addressed. Uniform water and fat separated 3D T_2-weighted images are demonstrated in various anatomies including breast, abdomen, knee, and ankle in less than 9 minutes of scan time.

MATERIALS AND METHODS

Modulated Refocusing Flip Angle 3D-FSE

The 3D-FSE sequence with modulated refocusing FAs and very long echo trains used in this work was based on a previously described technique (8). The refocusing FA train and the corresponding simulated signal at each CPMG echo are illustrated in Fig. 1. Following a 90° excitation pulse, the refocusing FA train begins at first FA (α_{first}), and then rapidly decreases to a minimum FA (α_{min}). The FAs during this rapid transition are calculated to maintain the signal at pseudosteady state (PSS)(23) and signals are not acquired during this transition (first four echoes). For the remainder of the echo train the refocusing FAs are gradually increased to a center FA (α_{center}), and then to a last FA (α_{last}) with the intermediate refocusing FAs calculated using the algorithm developed by Busse et al (8).

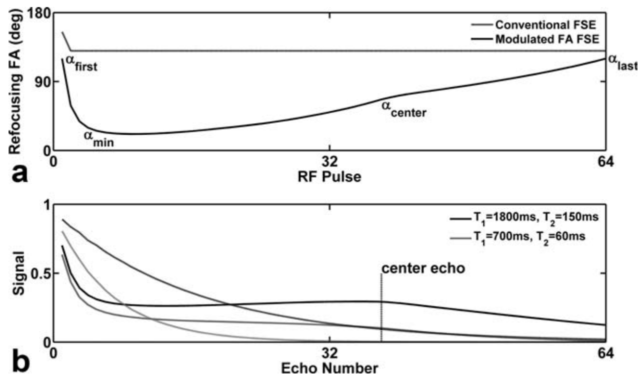

Figure 1. (a) Refocusing flip angles of a conventional FSE and modulated FA FSE and **(b)** the corresponding simulated signals with the assumed T_1 and T_2 values. The low refocusing FAs at the beginning of the train slow the effective rate of signal decay and are gradually increased to counteract the decay during the later part of the echo train with the modulated FA FSE. The parameters used for the simulation are: α_{first} = 120°, α_{min} = 20°, α_{center} = 70°, α_{last} = 120°, and CPMG echo spacing = 10 msec. For the conventional FSE, a stabilization refocusing FA of 155°, followed by a constant refocusing FA of 130° was used.

The initially reduced refocusing FAs cause a portion of the magnetization to be stored along the longitudinal axis, which decays at the slower T_1 rate. This stored magnetization is then recalled into the signal pathway by increasing the FA in the later part of the echo train. Hence, the effective rate of signal decay is significantly reduced compared to the rapid T_2 decay seen with conventional FSE (Fig. 1b). This allows the use of very long CPMG echo trains with modulated FA 3D-FSE. The explicit control of α_{min}, α_{center}, and the CPMG echo train length (ETL) provides increased flexibility in varying the signal decay and thus the effective echo time (TE_{eff}) and SNR.

IDEAL

The IDEAL water/fat imaging technique exploits the resonance frequency differences between water and fat to differentiate water signal from fat signal. The frequency difference is measured as phase difference in the acquired data. IDEAL relies on a minimum of three gradient-recalled echoes at different water–fat phase shifts acquired asymmetrically with respect to the CPMG echo (19). The phase encoding for each of the shifted gradient-recalled echoes is the same, thus the difference in phase results only from the off-resonance precession. Using the complex images from the gradient-recalled echo shifts, the local field map (B_0 inhomogeneity) is determined using a region-growing approach (24). The field map is then demodulated from the signal in the source images, enabling the signal to be decomposed into separate water and fat

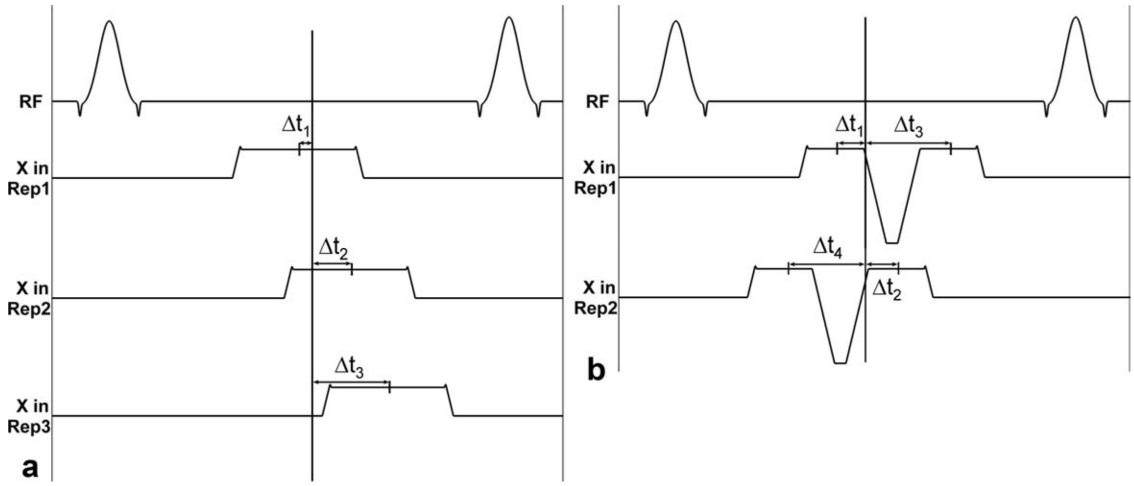

Figure 2. A pair of refocusing RF pulses and the corresponding readout gradients used in separate repetitions. Δt_i represents the echo shift with respect to the CPMG echo to impart the phase shift between water and fat. **a**: One gradient echo per CPMG echo approach, where IDEAL gradient echoes at three different shifts are acquired in separate repetitions. This approach requires three repetitions to acquire the data for a given set of phase encodes. **b**: Two gradient echoes per CPMG echo approach, where echoes 1 and 3 are acquired in the first repetition and echoes 2 and 4 are acquired in the second repetition. Using this approach, all four echoes are used in a 4-point IDEAL reconstruction.

signals using a least-squares matrix inversion. Additionally, to maximize SNR performance of the water–fat decomposition for all combinations of water and fat within a voxel, the asymmetric echoes are acquired at water–fat phase shifts of $-\pi/6$, $+\pi/2$, and $+7\pi/6$ with respect to the CPMG echo (20).

Integration of Modulated FA 3D-FSE with IDEAL (3D-FSE-IDEAL)

In an FSE sequence, multiple CPMG echoes are generated each repetition and one line of *k*-space is acquired per CPMG echo. For an IDEAL acquisition, the gradient-recalled echo is shifted with respect to CPMG echo. During data acquisition, multiple gradient echoes with respect to a particular CPMG echo are acquired with the same line of *k*-space (ie, same phase encoding gradient to generate a source image at each echo shift). Various methods have been previously developed to acquire gradient echoes with different shifts in an FSE-based sequence for water–fat separation (13,25). We implemented two alternative approaches for comparison.

Our first approach, which we refer to as “one gradient echo per CPMG echo” used the method described by Hardy et al (13) and is shown in Fig. 2a. In three successive repetitions, the gradient echoes were shifted to $-\pi/6$, $+\pi/2$, and $+7\pi/6$ with respect to the CPMG echo. The effective gradient echo shift spacing of $2\pi/3$ maximized the SNR of the processed water image for all combinations of water and fat within a voxel (20). To accommodate the echo shifts, the spacing between the refocusing RF pulses had to be increased by twice the largest echo shift so that the CPMG condition was maintained throughout the echo train. For example, at 1.5 T the radiofrequency (RF) echo spacing was increased by 5.6 msec (twice the $+7\pi/6$ echo shift). This increased RF spacing limits the number of CPMG echoes that can be acquired in an echo train without significant signal decay. To compensate, we used a combination of two approaches: First, the minimum refocusing FA (α_{min}) was reduced from 35° to 20°. Since the reduced refocusing FAs allow a greater fraction of the magnetization to spend more time along the longitudinal axis, the effective rate of signal decay was substantially slowed. Second, the CPMG ETL was reduced to acquire data before substantial signal decay. With the one gradient echo per CPMG echo approach using a reduced α_{min}, the total scan time of 3D-FSE-IDEAL was approximately three times longer than the standard 3D-FSE acquisition.

Our second approach, which we refer to as “two gradient echoes per CPMG echo,” was implemented to reduce the total scan time. In two successive repetitions, four phase-shifted gradient echoes were acquired, as shown in Fig. 2b, decreasing the total scan time by one-third. Gradient echoes at shifts of $-\pi/6$ and $+7\pi/6$ (with respect to the CPMG echo) were acquired in the first repetition, while gradient echoes at shifts of $-5\pi/6$ and $+\pi/2$ were acquired in the next repetition. For our preliminary implementation, we used the same gradient echo spacing of $2\pi/3$ such that the increase in RF echo spacing is the same compared to the “one gradient echo per CPMG echo.” This provided the additional echo at $-5\pi/6$, which has an equivalent phase shift of $+7\pi/6$. All four gradient echoes (at $-5\pi/6$, $-\pi/6$, $+\pi/2$, and $+7\pi/6$) were used for water–fat separation using a 4-point IDEAL algorithm. The use of four gradient echoes provided an improvement in the SNR of the decomposed water and fat images compared to the conventional 3-point IDEAL (26). For cases where the selected frequency (readout) resolution was large and/or receiver bandwidth low, a fractional readout acquisition was used to maintain the $+4\pi/3$ gradient echo spacing. In such

Table 1
Image Acquisition Protocol

Anatomy (fig. #)	FOV (mm^2) frequency × phase	Matrix	Slice thickness (mm)	No. of slices	TR (msec), TE_{eff} (msec)	ETL	BW (kHz)	Net acceleration factor	No. of gradient echoes per CPMG echo	Scan time (min)
Breast (Fig. 3)	180 (A/P)× 300 (R/L)	192 × 320	2.0	92	1500, 98	57	±41.67	3.6	1	8:32
Abdomen (Fig. 4)	300 (R/L)× 210 (A/P)	256 × 112	4.0	48	Resp. Trig, 98	27	±83.33	2.8	2	7:01
Knee (Fig. 5)	160 (S/I)× 160 (A/P)	256 × 256	1.0	120	2000, 99	57	±50.00	3.6	2	7:51
Ankle (Fig. 6)	140 (S/I)× 140 (A/P)	256 × 256	2.0	48	2000, 99	61	±62.50	1.8	2	5:23

cases, the IDEAL reconstruction utilized homodyne processing (27) to reconstruct the water and fat separated images to their full resolution.

MRI Experiments

All experiments were performed on a 1.5 T HDx scanner (GE Healthcare, Waukesha, WI). The Institutional Review Board approved the volunteer studies and written informed consent was obtained from the volunteers prior to scanning. The modulated FA 3D-FSE-IDEAL was evaluated on various anatomies including breast, abdomen, knee, and ankle to acquire robust 3D T_2-weighted water and fat-separated images in clinically feasible scan times.

The echo times corresponding to the $-5\pi/6$, $-\pi/6$, $+\pi/2$, and $+7\pi/6$ water–fat phase shifts at 1.5 T field strength are −2.0 msec, −0.4 msec, +1.2 msec, and +2.8 msec, respectively, with respect to the CPMG echo. Based on the frequency (readout) resolution, receiver bandwidth, gradient strength, and the gradient slew rate, the pulse sequence was implemented to determine whether two gradient echoes per CPMG echo (for example, gradient echoes 1 and 3 at 3.2 msec apart) with full readout could be acquired. If not, the sequence next determines whether two gradient echoes per CPMG echo with fractional readout could be acquired. If not, the sequence automatically reverted to the one gradient echo per CPMG echo acquisition mode.

All acquisitions were performed using phased-array coils and an autocalibrated 2D parallel imaging (28) method, with an outer acceleration factor of 2 along the phase encoding direction and an outer acceleration factor between 1 and 2 along the slice encoding direction. A linear view ordering along k_y(8) was used with the following refocusing FAs: $\alpha_{first} = 120°$, $\alpha_{min} = 20°$, $\alpha_{center} = 70°$, and $\alpha_{last} = 120°$. For abdominal imaging, the α_{min} was increased to 45° to reduce the sensitivity to motion (29,30). The remaining acquisition parameters for various protocols are listed in Table 1. At the end of the acquisition the source images at each echo shift were first reconstructed, followed by the IDEAL processing to generate water-only, fat-only, in-phase, and out-of-phase images.

RESULTS

3D T_2-weighted images with uniform water–fat separation were successfully acquired using 3D-FSE-IDEAL in clinically acceptable scan times (Table 1). Figure 3 shows example breast images, acquired in

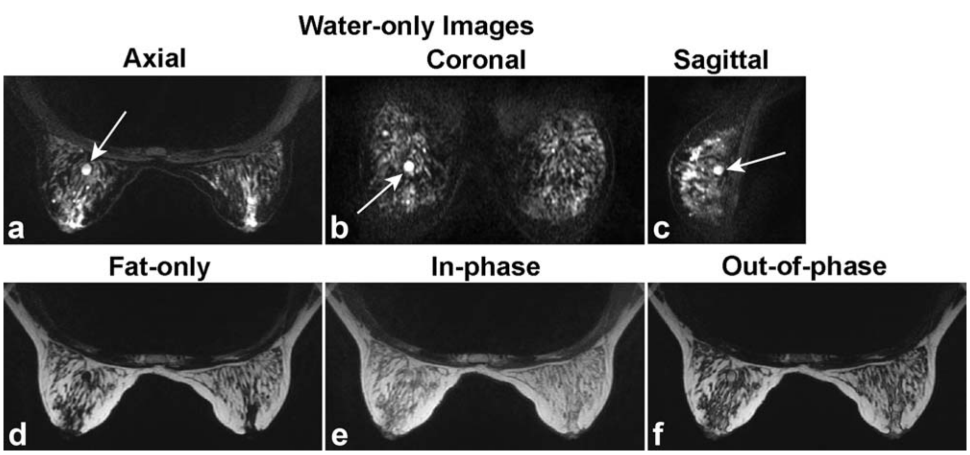

Figure 3. Breast images using one gradient echo per CPMG echo approach in a 8-minute, 32-second axial plane acquisition with 0.9 × 0.9 × 2.0 mm^3 resolution, reconstructed to 0.6 × 0.6 × 1.0 mm^3. Images were acquired in the axial plane (**a**), and reformatted to coronal (**b**) and sagittal (**c**) orientations. 3D acquisition provides high spatial resolution in all orientations (a–c) and IDEAL processing provides multiple contrasts (a,d–f) in a single acquisition. An incidental cyst is observed in the right breast, which is clearly depicted in all orientations (arrows).

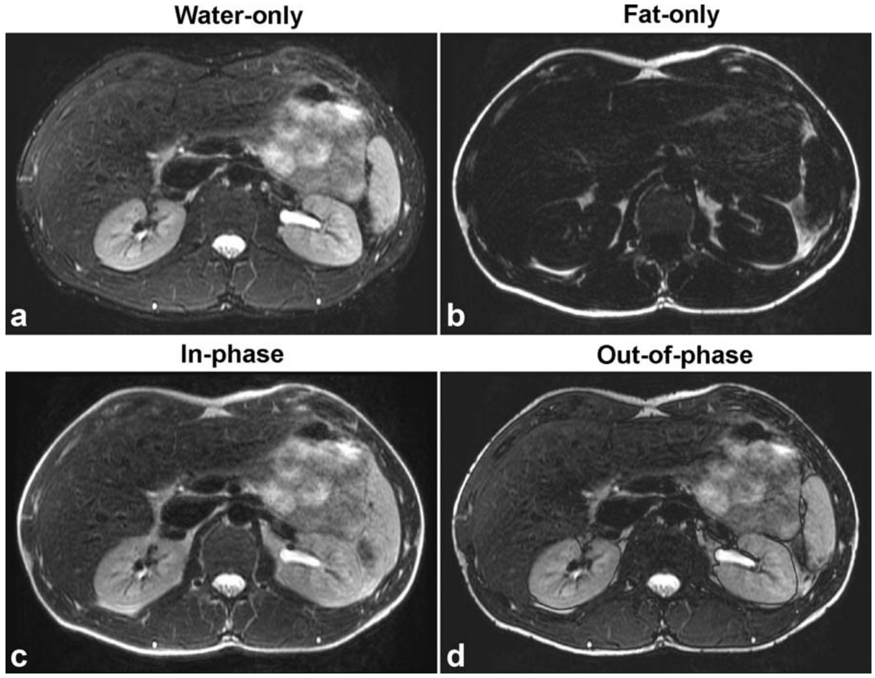

Figure 4. Abdomen images in the axial plane showing uniform water–fat separation and a true spatial resolution of $1.2 \times 1.9 \times 4.0$ mm^3, interpolated to $0.6 \times 0.9 \times 2.0$ mm^3. From the water-only (**a**) and fat-only (**b**) images, inphase (**c**) and out-of-phase (**d**) images were also reconstructed. These images were acquired using the two gradient echoes per CPMG echo approach in 7 minutes of free breathing.

an axial orientation and reformatted into coronal and sagittal planes. Uniform water–fat separation was observed throughout the entire volume and processing with the multipeak IDEAL (31) algorithm achieved very high contrast between water and fat (Fig. 3a). Using water-only (Fig. 3a) and fat-only (Fig. 3d) images, in-phase (Fig. 3e) and out-of-phase (Fig. 3f) images were also reconstructed, thus providing multiple contrasts and multiple orientations from a single acquisition. These images were acquired using the one gradient echo per CPMG echo approach and the entire 3D volume was acquired in an 8-minute, 32-second scan time with a spatial resolution of $0.9 \times 0.9 \times 2.0$ mm^3.

Figure 4 shows a single abdominal slice from a volume acquired in the axial plane. These images were acquired using respiratory and peripheral gating using the two gradient echoes per CPMG echo approach and fractional readout, with an approximate repetition time of 4 seconds. Due to the increased sensitivity of low refocusing FA FSE sequences to motion (29,30), the acquisition was cardiac gated and the α_{min} was increased to 45°(as opposed to 20°). The increase in α_{min} forced a reduced ETL of 27 to achieve a TE_{eff} of 98 msec. However, with the two gradient echoes per CPMG echo, whole abdomen coverage with uniform water–fat separation at a resolution of $1.2 \times 1.9 \times 4.0$ mm^3, interpolated to $0.6 \times 0.9 \times 2.0$ mm^3, was acquired in a 7:01-minute scan time.

Knee images acquired in the oblique-sagittal orientation and reconstructed into coronal and axial planes are shown in Fig. 5. High spatial resolution is critical for clinical evaluation of knee disorders and fat-suppressed and nonfat-suppressed images are usually required. 3D-FSE-IDEAL provides both fat-suppressed (water-only, Fig. 5a–c) and nonfat-suppressed (in-phase, Fig. 5d–f) images with a spatial resolution of $0.6 \times 0.6 \times 1.0$ mm^3 in a single acquisition under 8:00 minutes. The images were processed with multipeak IDEAL, yielding high contrast between water and fat.

Figure 6 shows ankle images acquired in the sagittal plane. Uniform water–fat separation was achieved in this area of high B_0 variation. The images show an in-plane resolution of 0.5×0.5 mm^2 and a through-plane resolution of 2.0 mm slice thickness (reconstructed to 1.0 mm) in a 5:23 minute scan time, covering the entire ankle with 48 slices. These images were also acquired using the two gradient echoes per CPMG echo approach and fractional readout.

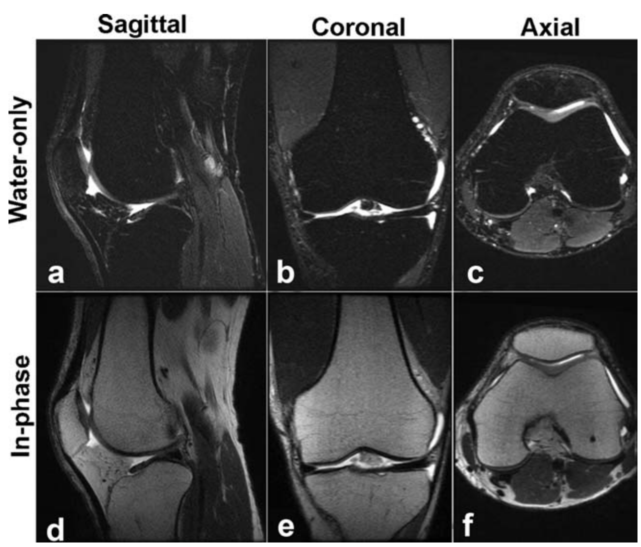

Figure 5. Knee images with and without fat suppression in a single acquisition using 3D-FSE-IDEAL. Images show uniform fat suppression and a spatial resolution of $0.6 \times 0.6 \times 1.0$ mm^3, interpolated to $0.3 \times 0.3 \times 0.5$ mm^3. These images were acquired with the two gradient echoes per CPMG echo approach in 7:51 minutes.

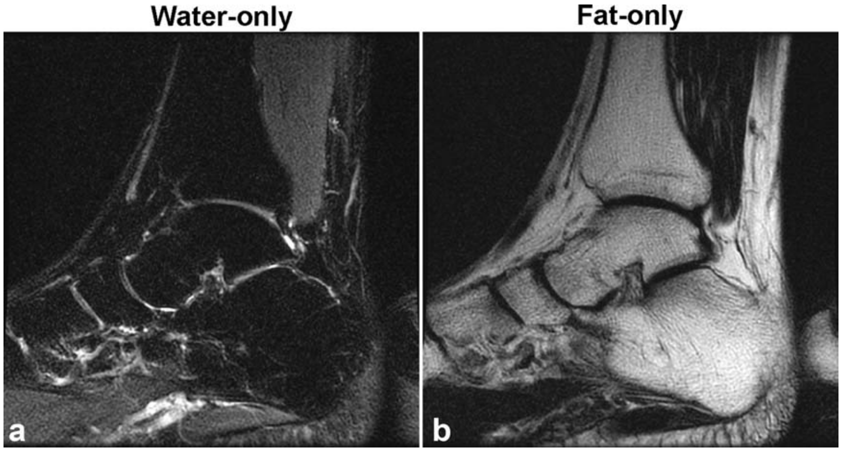

Figure 6. Ankle images showing uniform fat suppression. Images were generated from a single acquisition, obtained at a true spatial resolution of 0.55 × 0.55 × 2.0 mm^3, interpolated to 0.27 × 0.27 × 1.0 mm^3 through zero filling, covering the entire ankle in 5:23 minutes.

DISCUSSION

T_2-weighted image contrast is fundamental in clinical MRI, facilitating detection and characterization of abnormalities, such as identifying edema or distinguishing cysts from solid lesions. In the current clinical practice, T_2-weighted images are acquired as 2D stacks often in multiple orientations to capture the abnormal findings and better characterize them. Additionally, images with uniform fat suppression accompanied by nonfat-suppressed images are often critical, for example in the breast, when evaluating for fat necrosis. The single acquisition strategy demonstrated herein yields multifaceted contrast with high resolution, attributes that ensure excellent coregistration and cross-referencing of subsequent datasets that can be generated. In this work we have demonstrated such a 3D T_2-weighted acquisition with uniform water and fat-separated images in a single acquisition within clinically feasible scan times. This technique also reconstructs in-phase (or nonfat-suppressed) and out-of-phase images to provide multiple contrasts (water-only, fat-only, in-phase, and out-of-phase) in multiple orientations (for example, axial, coronal, and sagittal) in a single acquisition. 3D-FSE-IDEAL has the potential to replace multiple 2D acquisitions with and without fat suppression in clinical practice, thus improving scanning efficiency.

Compared to the original extended echo train 3D-FSE (8), the CPMG echo spacing in 3D-FSE-IDEAL was increased to accommodate the various echo shifts. Specifically, it was increased by twice the largest IDEAL echo shift (for example) $2 \times 7\pi/6$ (5.6 msec at 1.5T). This increased RF echo spacing limited the total number of echoes that could be acquired without significant signal decay. In our implementation of 3D-FSE-IDEAL, we addressed this by decreasing the minimum refocusing FA (α_{min}) to 20° and reducing the total number of RF echoes acquired per echo train. Because the reduced refocusing FAs allow a greater fraction of the magnetization to spend more time along the longitudinal axis instead of the transverse plane, this significantly slows the effective rate of signal decay. This allowed us to use extended echo trains on the order of 60 even with increased CPMG echo spacing while limiting blurring.

While the reduced α_{min} compensates for the increase in CPMG echo spacing, it imposes additional challenges. In an FSE sequence, reduced refocusing FAs increase the sensitivity to motion (29,30); for example, note the signal loss in the heart observed in the breast images (Fig. 3). While this may not be a significant issue for anatomies such as breast, knee, and ankle, in abdominal applications there is increased sensitivity potentially to respiratory, cardiac, and bowel motion. In our preliminary studies for the abdominal application, we increased the α_{min} to 45° and used both respiratory and peripheral pulse gating to synchronize the data acquisition to the quiescent period of cardiac and respiratory motion (Fig. 4). This provided abdominal images without signal loss. However, to maintain clinically desirable TE_{eff}, the ETL needed to be reduced, which in turn prompted a reduction in resolution to acquire the images in clinically feasible scan times. Compared to breath-hold 2D T_2-weighted imaging techniques with fat suppression (32), 3D-FSE-IDEAL in its current implementation may have limitations in general body imaging. Future implementations with navigator based triggering (33) may improve the reliability of this technique compared to respiratory triggering in body applications. Additionally, in cases where bowel motion could affect the image quality, antiperistaltics may be used to counter the effects of bowel motion.

The use of parallel imaging helped to keep scan times clinically feasible. Although parallel imaging comes with a penalty in SNR, the effective averaging that occurs as part of IDEAL largely offsets the decrease in SNR.

All of our preliminary studies were performed at 1.5 T. The extension to 3.0 T is relatively straightforward with the one gradient echo per CPMG echo approach. In fact, this provides an added benefit of limited increase in CPMG echo spacing because the $2 \times 7\pi/6$ increase is only 2.8 msec at 3.0 T compared to 5.6 msec at 1.5 T (water–fat frequency shift is 420 Hz at 3.0 T, while it is 210 Hz at 1.5 T). This allows the use of higher ETL and thus reduced scan times at 3.0 T with the one gradient echo per CPMG echo approach. The two gradient echoes per CPMG echo approach is more challenging at 3.0 T, however. The $4\pi/3$ spacing required between successive gradient echoes within the interval between refocusing RF pulses (for example, gradient echoes 1 and 3) would be only 1.6 msec at 3.0 T compared to 3.2 msec at 1.5 T. This would be specifically challenging for applications such as the knee, which uses small FOV and high spatial resolution.

We used only unipolar readouts in our implementation with the two gradient echoes per CPMG echo approach. Alternative data acquisitions could potentially use bipolar readouts (26); however, that would require additional phase correction due to the alternating polarities of the readout gradients (26,34). Furthermore, it would also be challenging to acquire the successive echoes at $2\pi/3$ gradient echo spacing (1.6 msec at 1.5T and 0.8 msec at 3.0T).

In conclusion, we have developed a robust technique to acquire 3D T_2-weighted images with uniform water and fat separation in clinically feasible scan times. From a single acquisition, this technique provides multiple contrasts that can be reformatted in any orientation. This technique has the potential to replace multiple 2D acquisitions with and without fat suppression, thus increasing scanning efficiency.

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