Bipolar 3D-FSE-IDEAL: Fast Acquisition of Volumetric T_2-Weighted Fat and Water

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Introduction: T_2-weighted images, often acquired as 2D stacks in multiple orientations, are used in clinical practice to distinguish fluid-filled cysts from malignant lesions. For anatomies such as breast, uniform fat suppression is also critical to detect subtle edema and to differentiate and characterize cysts. Recently, there has been a focus to acquire fat-water separated 3D T_2-weighted images in a single acquisition (1, 2) by integrating 3-point (IDEAL) (3) or 2-point Dixon (4) chemical shift imaging with 3D-FSE-Cube (5). These 3D-FSE techniques (1,2) acquired multiple images required for fat-water separation with a "unipolar" readout in different repetition times. However, this prolongs scan times compared to traditional fat-suppressed acquisitions. Here, we use a "bipolar" acquisition to acquire all required echoes in a single repetition. A novel 2D phase correction method is used in addition to previously reported 1D phase correction (6) to eliminate phase errors that arise from the alternating polarities of the readout gradients. High-resolution 3D T_2-weighted images in breast and knee applications with uniform fat-water separation are demonstrated in less than 5-minute acquisitions.

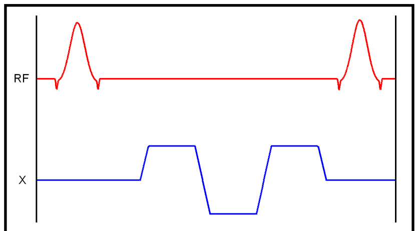

Fig. 1. A pair of RF refocusing pulse and the corresponding bipolar readout (X) gradient

Methods: A bipolar readout gradient with three echoes was implemented between each pair of refocusing pulses (fig. 1). Prior work has shown that echo shifts of $-\pi/6$, $+\pi/2$, and $+7\pi/6$ ($2\pi/3$ gradient echo spacing) maximize SNR for all combinations of fat and water (7). In cases where the minimum achievable gradient echo spacing exceeds $2\pi/3$, we have implemented a flexible echo timing strategy that provides a trade-off between SNR and spatial resolution. The third gradient echo is fixed at $+7\pi/6$ and the remaining two echoes are acquired at the minimum echo spacing allowed by the gradient performance, with a maximum of π spacing. This combination provides SNR efficiency of 90-100% of optimal, while still achieving uniform fat-water separation. For 2D phase correction, low-resolution reference data with reversed gradient polarities at each phase shift were collected. Using the pairs of low-resolution data with opposite polarities, the 2D phase errors were estimated and corrected.

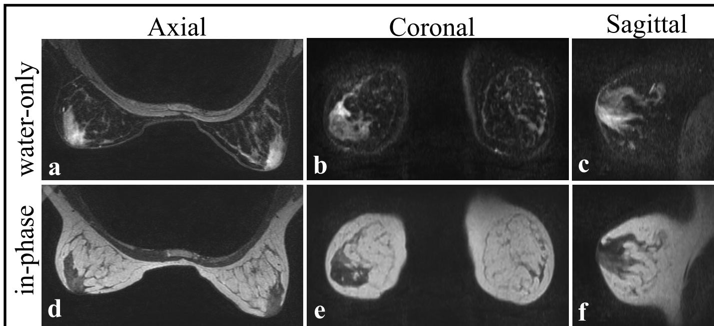

Fig. 2. High-resolution 3D T_2-weighted water-only and in-phase breast images acquired in scan time of 3:31 minutes.

3D-FSE-Cube-IDEAL with bipolar acquisition was implemented on a 1.5T HDx scanner (GE Healthcare, Waukesha, WI). The sequence was evaluated on breasts and knees in volunteers (with IRB approval) using 8-channel coils with ARC parallel imaging (8) (R=2×2). Parameters for axial acquisitions of the breasts were: TR = 2000 ms, TE_{eff} = 98 ms, BW = ±62.5 kHz, ETL = 60, matrix = 192×320×68, FOV = 190×300×163 mm^3 (acquired resolution of 1.0×1.0×2.4 mm^3). Gradient echo spacing achieved a $4\pi/5$ fat-water phase shift and scan time for complete coverage of both breasts (including the low-resolution reversed gradient polarity data) was 3:31 minutes. Parameters for oblique acquisition of knees were: TR = 2000 ms, TE_{eff} = 98 ms, BW = ±62.5 kHz, ETL = 56, matrix = 224×224×76, FOV = 160×160×122 mm^3 (acquired resolution of 0.7×0.7×1.6 mm^3). Gradient echo spacing achieved a fat-water phase shift of π and scan time for complete coverage of the knee was 3:37 minutes.

Results: Fig. 2 shows high-resolution T_2-weighted water-only (reconstructed using multi-peak IDEAL (9)) and "synthesized" in-phase (water+fat) breast images that were acquired axially (a, d) and reformatted into coronal (b, e) and sagittal (c, f) planes. Reconstructed image quality is excellent and the signal in the water-only images is uniform out to the axillae. Similarly, fig.3 shows water-only and in-phase images of the knee in standard orientations. Uniform fat suppression was achieved throughout the entire volume with 2D phase correction, even in the oblique acquisition. For the breasts, scan time was 3:31, compared to 8:17 for the equivalent scan with a single "unipolar" gradient echo per repetition (58% reduction in scan time). For the knee, the scan time was 3:37, compared to 8:05 for the equivalent scan with a single "unipolar" gradient echo per repetition (55% reduction in scan time).

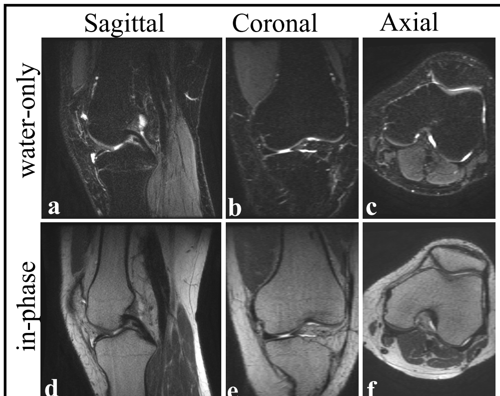

Fig. 3. High-resolution 3D T2-weighted water-only and in-phase images of the knee acquired in an oblique-sagittal orientation in scan time of 3:37 minutes.

Discussion: Our bipolar 3D-FSE-IDEAL implementation acquires all three gradient echoes required for IDEAL processing in a single repetition. This efficient strategy reduces scan time significantly, making it similar to a standard fat-suppressed acquisition. The IDEAL approach offers robust fat-water separation in regions with significant B_0 inhomogeneities such as the breasts, and provides in-phase and out-of-phase images. The 2D phase correction method along with the flexible echo timing strategy makes 3D T_2-weighted imaging with uniform fat suppression a clinical reality.

Reference: 1) Madhuranthakam et. al. ISMRM 09; p. 4131. 2) Prato et. al. ESMRMB 09; p. 18. 3) Reeder et. al. MRM 05; 54: p. 636. 4) Ma et. al. MRM 07; 58: p. 103. 5) Busse et. al. MRM 08; 60: p. 640. 6) Li et. al. MRM 07; 57: p. 1047. 7) Pineda et. al. MRM 05; 54: p. 625. 8) Beatty ISMRM 07; p. 1749. 9) Yu et. al. MRM 08; 60: p. 1122.