On the Application of the DIXON Method in Balanced SSFP Imaging

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INTRODUCTION

The basic principle of the DIXON method for water-fat decomposition has been applied in balanced steady-state free precession sequences (bSSFPs) by exploiting the spin-echo-like signal behavior [1] with single- [2] or multiple-data acquisition [3,4], providing superior SNR over non-balanced SSFP sequences such as FISP and GRASS. In this approach an implicit assumption is made that no temporal shift of the echo occurs [2,3,4]. However, if the echo does shift from t = TR/2, the integrity of the water-only and fat-only images can be degraded.

The purpose of the study was to examine the consequence of neglecting such echo-shift in bSSFP on water-fat decomposition by using the iterative least-squares estimation method (ILSEM) [4] in combination with trueFISP. The ILSEM is particularly beneficial for a multipoint-DIXON+bSSFP combination as it imposes less restriction on the choice of TEs thereby minimizing the TR increment necessary for data acquisition at multiple points and consequently avoiding banding artifacts.

METHODS

Theoretical and Numerical Consideration: Unlike in FISP and GRASS, in bSSFP off-resonant spins possess initial phase that is a function of TR, T2 and offset frequency, f [5,6]. The role of such initial phase is to prepare individual spin isochromats in such a way that they form an echo at around t = TR/2. It is similar to a spin-echo [1,6], but is distinguished from that in conventional SE or FSE sequences in that 1) its temporal location varies depends on T2 and f of spins as well as TR, and 2) for a given TR and T2 the phase of the refocused magnetization is determined by f [1]. For water with small f ($|f| < 1/2\pi TR$) and T2 >> TR, the echo formation can be approximated to take place at t = TR/2 (to be termed as TR/2-approximation). However, due to the large chemical-shift of fat and T2 of these two spin species that can be significantly different from each other depending on ROI, the TR/2-approximation can result in error in water-fat decomposition and consequently in the estimation of the fat-to-water ratio. For instance, Fig.1 illustrates the degree of the echo-shift from t = TR/2 (TR = 5.5 ms assumed) for a water band (-20~20 Hz) and a fat band (-240 ~ - 200 Hz) at 1.5T. For water and fat both with TE = 50 ms the echo is shifted from t = TR/2 by 0.16 ms and 0.28 ms, respectively, in which case the TR/2-approximation results in unwanted phase accumulation of only ~ 1° for water magnetization but as much as 24° for fat magnetization. Thus, a desired configuration of water and fat magnetization vectors is not achieved precisely in this case. As T2 and f of water and fat can vary across the pixels in an image, the performance of any DIXON+bSSFP combinations can differ from pixel to pixel in the resultant water-only and fat-only images.

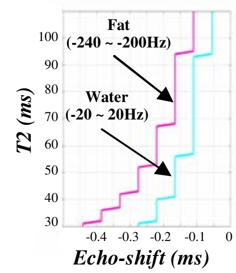

Fig. 1 Calculated Water and Fat Echo-Shift from t = TR/2 in trueFISP as a Function of T2 and Offset-Frequency

Experiment and Data Analysis: To demonstrate the consequence of the TR/2-approximation on water-fat decomposition, three-point DIXON data were collected from the abdominal region of healthy male volunteers using trueFISP (TEs = 1.49/2.69/3.89 ms, Δ = 1.2 ms and TR = 5.38 ms; the second TE = TR/2). Two cylindrical phantoms were made, one containing water doped with Gadolinium DTPA (0.95 mM) and the other containing olive oil. Both phantoms were placed within the FOV. All experiments were conducted on a 1.5T Siemens Sonata scanner with a phase-arrayed, torso coil (USA Instruments, Inc.). A generic trueFISP sequence was modified for adjustable TEs. Other sequence parameters are: matrix size = 144x256, flip angle = 55°, 14 slices with the thickness of 10 mm, 1 average. All images were reconstructed from raw data according to the ILSEM algorithm for multicoil (4 channels) data acquisition [4] using MATLAB™ (MathWorks Inc.). The signal from the water phantom and the oil phantom in the resultant water-only and fat only-images were analyzed with TE2 varying from -1.0 ms to 1.0 ms with a step size of 0.05 ms. Here, the TE2 is the second echo time that needs to be prescribed in the ILSEM post-data processing algorithm (TE1 and TE3 prescribed as TE2 - Δ and TE2 + Δ, respectively) and prescribing the TE2 as 0 ms corresponds to the TR/2-approximation in this study. From these results, the fat to water ratio was also calculated for the phantoms only.

RESULTS

Fig.2(a) illustrates the variation of the signal intensity of the phantoms in the water-only image as a function of the prescribed TE2 (each curve normalized to its own maximum except the difference curve). While the water signal is stable, the oil signal changes drastically. The image when bSSFP is treated as an ordinary gradient echo sequence is shown in Fig.3(a) for which spin dephasing is assumed to initial at t = 0 as in FISP. The residual signal from the oil phantom, subcutaneous fat and some of intra-abdominal adipose tissue are clearly visible. According to Fig.2(a), the best water-only image (maximum difference between water and oil signal) specifically for the phantoms is obtained when the TE2 is set to 0.15 ms instead of 0 ms. However, that value is not necessarily optimal for other regions of the image, and as a result the residual fat signal in the abdomen still persists (bottom of Fig.3(b)). As well, upon the TR/2-approximation (bottom of Fig.3(c)), the residual fat signal in the abdomen is well suppressed but instead the oil phantom signal returns, when the fat-to-water ratio for these phantoms already changes by 6% (Fig.2(b)).

CONCLUSION

For superior SNR bSSFP sequences are popularly combined with the DIXON method or its variants for water-fat decomposition. Nonetheless, the performance of any DIXON+bSSFP combinations can differ from pixel to pixel in the resultant water-only and fat-only images due to the temporally variable echo formation in the sequences. The consequence of such echo-shift will be more significant at higher field due to shortened T2 and more severe field-inhomogeneity therein.

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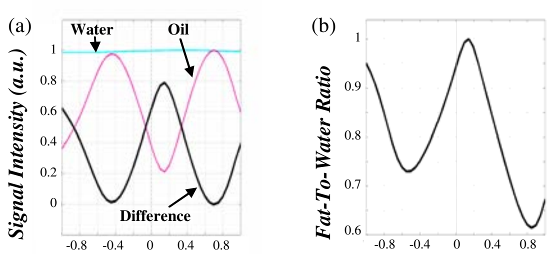

Fig. 2 (a) Modulation of Signal from Water and Oil Phantoms in the water-only image as a Function of the Prescribed TE2 in the Image Reconstruction. (b) Resultant Change in Fat-To-Water Ratio

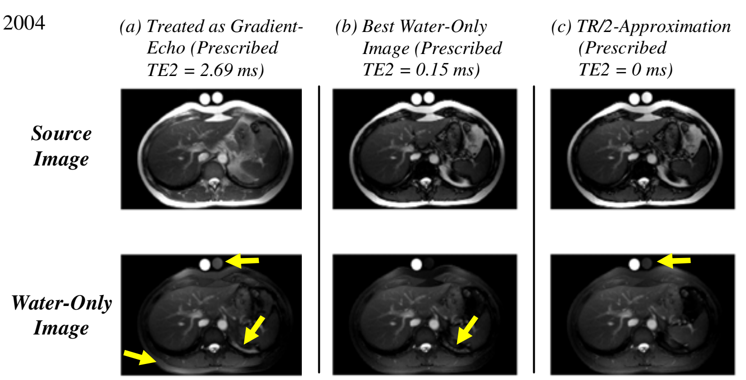

Fig. 3 Three-Point DIXON Abdominal Images Reconstructed by Using the Iterative Least-Squares Estimation Method. The signal from the oil phantom (right) and residual fat modulate depending on the prescribed TE2 in the post-data processing algorithm.