行政院國家科學委員會專題研究計畫　成果報告

快速穩定態磁振造影及其臨床應用之研究(2/2)

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快速穩定態磁振造影及其臨床應用之研究(2/2)
Rapid steady-state MR imaging and its clinical applications (2/2)

計畫編號：NSC 92-2218-E-002-017
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一、中文摘要

本研究展示穩定態自由旋進影像中水與脂肪信號分離之可行性。其中心思想為，在採用 TE = TR/2 之穩定態自由旋進技術中，相位角相對於射頻脈衝基本上只允許兩種角度的可能：亦即 0^0 與 180^0。利用此種特性，吾人得以利用中心頻率偏移的細部調整，在相同的影像條件之下達到水與脂肪同相（in-phase）或反相（out-of-phase）的影像，因此，一般磁振造影所使用的迪克遜法（Dixon method）便可以應用於此種技術中，經由複數影像的相加與相減達成水與脂肪信號的分離。在本計畫中，掃瞄參數 TR 與中心頻率偏移量經由理論計算加以最佳化，同時並在 3.0 Tesla 磁振造影系統上取得八位志願受試者腹部之二維穩定態自由旋進影像以驗證理論的推測。實驗結果證實本方法幾可達成接近完全的脂肪信號抑制，並且比商業化的技術具有更佳的軟組織對比。

關鍵詞：脂肪與水分離、迪克遜法、同相反相影像、穩定態快速成像。

Abstract

The feasibility of fat/water separation using the balanced steady-state free precession (SSFP) technique is demonstrated. The key idea is based on the observation that at the nominal values of TE = TR/2 in SSFP imaging, phase coherence could be achieved at essentially only two orientations, namely 0^0 and 180^0 relative to the RF pulses in the rotating frame, under the assumption of TR << T2 and independent of the steady-state free precession angle. This property allows in-phase and out-of-phase SSFP images to be obtained by proper choices of the center frequency offset, hence permitting the Dixon subtraction method to be utilized for effective fat/water separation. The TR and frequency offset for optimal fat/water separation are derived from theories. Experimental results on healthy subjects using a 3.0 Tesla system show that nearly complete fat suppression can be accomplished.

Keywords: Fat-water separation, Dixon method, in-phase out-of-phase images, steady-state free precession.

二、緣由與目的

The advantage in signal-to-noise efficiency of balanced steady-state free precession (SSFP) imaging (also denoted as TrueFISP for true Fast Imaging in Steady-state Precession, balanced FFE for balanced Fast Field-Echo, or FIESTA for Fast Imaging Employing STeady-state Acquisition by different manufacturers) has made itself an attractive technique in clinical practice. In certain situations, the signal from fat protons is a major source of interference hindering unambiguous image interpretation. This is understood because fat has a higher T2/T1 value compared with parenchymal tissues, which corresponds to bright steady-state signals on SSFP images (1). Therefore for applications in SSFP imaging that intend to highlight fluids with large T2/T1 values such as angiography, myelography, or MR cholangiopancreatography (MRCP), elimination of the fat signals becomes an essential issue.

In a recent work, it was shown that the SSFP images exhibit spin-echo-like behavior, where spin isochromats at similar resonant frequencies show phase coherence at either 0^0 or 180^0 relative to the RF pulses at the time TR/2, the nominal TE in SSFP imaging (2). For off-resonance species such as fat relative to water, the SSFP angle (i.e., the precession phase angle for the spin isochromats within one TR in the rotating frame) can be manipulated via an adjustment of the center reference frequency, which in turn determines the directional location for phase coherence in the rotating frame (2). This property leads naturally to the use of in-phase and out-of-phase images for Dixon addition/subtraction to achieve fat/water separation in SSFP imaging (3). In this study, we demonstrate the feasibility of fat/water separation in SSFP imaging using the Dixon method in vivo at high magnetic field (3.0 Tesla), with cautions in its usage and optimal off-resonance ranges described using both theories and experimental results.

三、方法

The key idea is based on the observation that at the nominal values of TE = TR/2, SSFP images show spin-echo-like phase coherence at only two orientations under the assumption of TR << T2 (2). The steady-state transverse magnetization immediately after the RF pulse, M_x^+ and M_y^+, can be expressed as a function of TR, T1, T2, flip angle α, and the SSFP angle θ within one TR, given by (1):

$$M_x^+ = M_0(1-E_1)(E_2 \sin\alpha \sin\theta)/D \qquad [1]$$

$$M_y^+ = M_0(1-E_1)[(1-E_2\cos\theta)\sin\alpha]/D \qquad [2]$$

with

$$\begin{aligned} D = & (1-E_1\cos\alpha)(1-E_2\cos\theta) \\ & -(E_1-\cos\alpha)(E_2-\cos\theta)E_2 \end{aligned} \qquad [3]$$

$$E_1 = e^{-TR/T1} \qquad [4]$$

$$E_2 = e^{-TR/T2} \qquad [5]$$

Equations [1] to [5] were used to calculate the signal intensity and phase angle for muscle (water) and fat at 3.0 Tesla as a function of center frequency offset from –200 Hz and +200Hz. A 180^0 phase alternation for the RF pulses was assumed, as is often used in SSFP imaging. The ranges of frequency offset which yielded low signal intensity for either water or fat were marked out as those “not recommended for SSFP Dixon imaging” because signal heterogeneity would likely cause imperfect signal cancellation in the Dixon method. “Low signal intensity” was defined as less than 70% of the SSFP signal at $\theta = 180^0$. For the remaining frequency offsets which provide fairly uniform signal for both water and fat, the phase angles of the two species were examined. The above process was repeated for TR = 2.0 to 7.0 msec. Therefore a graph was generated which showed the in-phase or out-of-phase behavior as a function of TR and frequency offset. The TR value showing equally wide ranges of frequency offset for both in-phase and out-of-phase behavior was regarded as the optimal TR for SSFP Dixon imaging, and was thus chosen for experiments. The middle frequency values in the offset ranges for in-phase and out-of-phase images were regarded as the optimal center frequency offsets because they are far from the null signal regions for fat and water.

Abdominal imaging was performed on eight healthy adults (seven male and one female, aged 23-38 years) who volunteered participation in this study. Experiments were performed on a 3.0 Tesla MR imaging system (Siemens Trio, Erlangen, Germany). Transaxial SSFP images at about the kidney levels were acquired using a two-dimensional TrueFISP sequence with TR/TE = 3.4/1.7 (TR chosen according to results obtained from the theoretical analysis), flip angle = 24^0, field-of-view = 340 mm, 256x256 matrix, slice thickness = 5 mm, signal averages = 4. The half-angle-half-TR preparation scheme was used before RF excitation, along with a linear phase encoding order. Note that at the matrix size chosen in this study, the image contrast can be regarded as largely dominated by the steady-state signal response (4). The body coil was used for signal receiving. Scan time was less than one second per slice for each signal average. Three-dimensional shimming was performed before SSFP data acquisition in all cases to ensure maximum field homogeneity. Off-resonance was achieved by adjusting the RF center frequency from –100 Hz to +100 Hz at 20 Hz step. The RF specific absorption rate was estimated with the manufacturer-supplied software such that the recommended FDA limitations were not exceeded. During imaging and shimming, the subjects were asked to hold their breath at end expiration to ensure consistent acquisition locations. The image raw data (before taking the absolute magnitude) were digitally transferred to a personal computer for calculation. Summation of in-phase and out-of-phase images yielded water-only image, whereas subtraction gave the fat-only image.

四、結果與討論

Figure 1 shows the phase behavior for muscle and fat at 3.0 Tesla as a function of TR and center frequency offset. The stripe-like regions correspond to those not recommended for use in Dixon imaging because the signals from either muscle or fat (or both) are close to zero and hence likely to cause imperfect signal cancellation or shimming difficulty. From Fig.1 it is seen that at TR equal to odd multiples of 2.24 msec (i.e., inverse of the chemical shift frequency), the SSFP images would always show out-of-phase behavior, consistent with results from a previous report (5). In contrast, at TR equal to even multiples of 2.24 msec, muscle and fat would always be in-phase. It thus becomes clear that the choice of TR = 3.4 msec (about halfway between 2.24 msec and 4.48 msec) is close to the situation where equal ranges of center frequency offset can be used to obtain both in-phase and out-of-phase images (vertical dashed line in Fig.1). A TR of 3.4 msec was hence selected for all experiments performed in this study. Furthermore, it is noticed that at TR = 3.4 msec, the frequency offsets of +80 Hz and –80 Hz are optimal for in-phase and out-of-phase imaging, respectively, because the obtained images would be relatively immune to intensity heterogeneity near the null signal points.

Figures 2a and 2b show the water-only and the fat-only images, respectively, obtained from the +80 Hz in-phase and the –80 Hz out-of-phase images. Nearly complete fat suppression can be seen in Fig.2a. Note that although the on-resonance image is also out-of-phase in characteristics, the presence of banding would result in incomplete fat cancellations, in good agreement with our theoretical prediction from Fig.1. Fig.2c is a fat-suppressed image on the same slice location, acquired via one single fat-suppression RF pulse followed by a two-dimensional SSFP readout with centric phase encoding (i.e., the manufacturer-supplied fat-suppression TrueFISP sequence). One in particular notices the change of image contrast in Fig.2c to proton-density-weighted, compared with the T2/T1-weighting in Fig.2a which provides much better contrast between muscle and the kidneys.

In this work we present a Dixon-based method for fat/water separation using in-phase and out-of-phase SSFP imaging. We have analyzed the in-phase/out-of-phase behavior as a function of TR and center frequency offset at 3.0 Tesla and also derived the TR and offset values optimal for SSFP Dixon imaging. Unlike the Dixon method used in conventional gradient-echo imaging (3), SSFP Dixon imaging employs the concept of spin-echo-like phase-coherence at TE = TR/2 (2), which in turn is dependent on the SSFP angle tunable via adjustments of the center reference frequency. One notices that for a wide range of SSFP angle, there are essentially only two orientations where phase coherence occurs, namely 0^0 and 180^0 relative to the RF pulses. Consequently the exact value of the off-resonance frequency chosen to form in- or out-of-phase images is not critically important, as long as the low-signal region can be effectively avoided (Fig.1). This can be evidenced from our experimental results, where nearly complete fat/water separation was achievable at ±80 Hz off-resonance, because these off-resonance frequencies corresponded in Fig.2 to situations where both fat and water signal phases were relatively insensitive to slight changes in the SSFP angle due to shimming imperfections.

In conclusion, we have successfully demonstrated the feasibility of fat/water separation in SSFP imaging based on the Dixon approach, and analyzed the in-phase and out-of-phase behavior as a function of TR and center frequency offset. The method is directly applicable on systems equipped with generic SSFP imaging sequence without the need for advanced pulse programming, and potentially allows for quantification of the fat/water contents even in the presence of partial volume effects. Attempts to applications in the clinical practice are currently underway.

五、參考文獻

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六、圖表（見下頁）

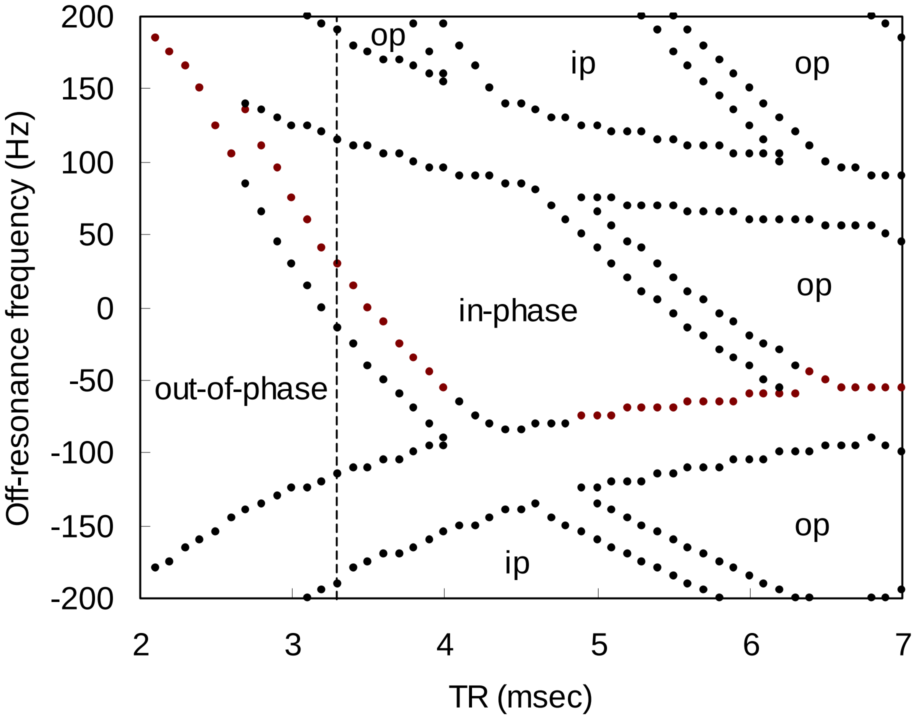

Figure 1. Graph showing the phase behavior for muscle and fat in SSFP images at 3.0 Tesla (flip angle = 24^0, 180^0 phase alternations for the excitation RF pulses) as a function of TR and center reference frequency offset. Abbreviations "ip" and "op" represent in-phase and out-of-phase for muscle and fat, respectively. The stripe-like regions correspond to those not recommended for use in Dixon imaging because the signals from either muscle or fat (or both) are close to zero and hence likely to cause imperfect signal cancellation or shimming difficulty. At TR equal to odd multiples of 2.24 msec (i.e., inverse of the chemical shift frequency), the SSFP images would always show out-of-phase behavior, whereas at TR equal to even multiples of 2.24 msec, muscle and fat would always be in-phase. The vertical dashed line corresponds to the experimental condition (TR = 3.4 msec, about halfway between 2.24 msec and 4.48 msec) used in this work, where different center frequency offsets yield half in-phase and half out-of-phase SSFP images and is thus optimal for Dixon imaging.

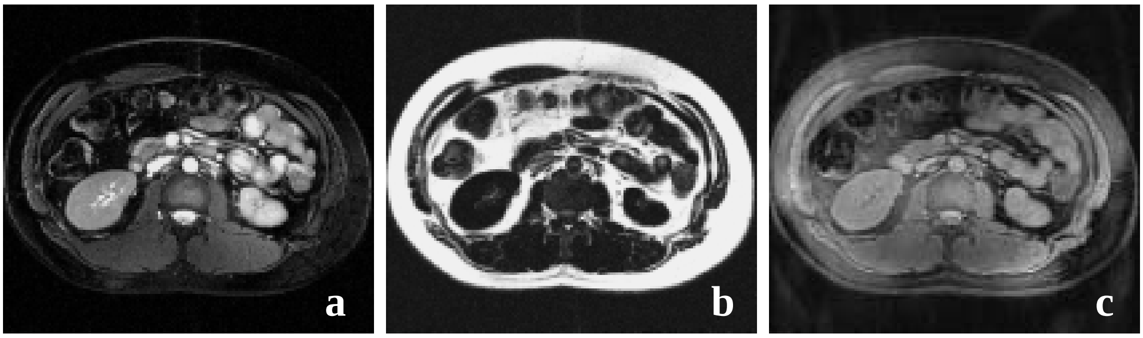

Figure 2. Water-only (a) and fat-only (b) SSFP images obtained using the Dixon method from the +80 Hz in-phase and the –80 Hz out-of-phase images in Fig.3. Shown in Fig.4c for comparison is a fat-suppressed image on the same slice location, acquired via one single fat-suppression RF pulse followed by a two-dimensional SSFP readout with centric phase encoding (manufacturer-supplied fat-suppression TrueFISP sequence). Note that the image contrast in Fig.4c is basically proton-density-weighted (transient-state contrast), as opposed to the better contrast (e.g., between muscle and kidney) provided by the steady-state T2/T1-weighting in Fig.4a.