Fat and Water Separation in Balanced Steady-State Free Precession Using the Dixon Method

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In this work the feasibility of separating fat and water signals using the balanced steady-state free precession (SSFP) technique is demonstrated. The technique is based on the observation (Scheffler and Hennig, Magnetic Resonance in Medicine 2003;49:395–397) that at the nominal values of TE = TR/2 in SSFP imaging, phase coherence can be achieved at essentially only two orientations (0° and 180°) relative to the RF pulses in the rotating frame, under the assumption of TR << T2, and independently of the SSFP angle. This property allows in-phase and out-of-phase SSFP images to be obtained by proper choices of the center frequency offset, and thus allows 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 from healthy subjects, using a 3.0 Tesla system, show that nearly complete fat suppression can be accomplished. Magn Reson Med 51:243–247, 2004. © 2004 Wiley-Liss, Inc.

Key words: fat–water separation; Dixon method; in-phase and out-of-phase images; steady-state free precession; frequency offset

The advantage of increased signal-to-noise ratio (SNR) efficiency in balanced steady-state free precession (SSFP) imaging (also denoted as true fast imaging in steady-state precession (TrueFISP), balanced fast field-echo (FFE), or fast imaging employing steady-state acquisition (FIESTA) by various manufacturers) has made this technique attractive for clinical applications. Examples of such applications include (but certainly are not limited to) cardiac imaging (1,2), angiography (3,4), gastrointestinal imaging (5,6), and fetal imaging (7). In certain situations, the signal from fat protons is a major source of interference that hinders our ability to interpret the image unambiguously. This is understood because fat has a higher T2/T1 value compared to parenchymal tissues, which corresponds to bright steady-state signals on SSFP images (8). Therefore, for SSFP imaging applications intended to highlight fluids with large T2/T1 values, such as angiography, myelography, and MR cholangiopancreatography (MRCP), it is essential to eliminate the fat signals.

Fat suppression in SSFP imaging can be accomplished by using frequency-selective RF pulses in every TR, similarly to the conventional approach used in spin-echo imaging (5). This method increases TRs that are ordinarily short in generic SSFP sequences, and thus increases total scan time by a noticeable factor. Alternatively, magnetization preparation during the steady state, which refers to the addition of one fat-suppression pulse every several TRs, has also been shown to be effective (9). The latter method is advantageous in that the scan time is not significantly increased, which is beneficial for 3D examinations. Other methods, such as linear combination SSFP (10) and fluctuating equilibrium MR (11), have been proposed that make use of the SSFP spectral profiles manipulated by different RF phase schemes to selectively reconstruct different spectral species. For 2D imaging, the use of a single fat-suppression RF pulse followed by a centric-ordered SSFP readout should serve the same purpose well, with the exception that the resulting image contrast is inevitably altered to proton-density weighting due to the transient-state signal behavior (12).

In a recent work, it was shown that SSFP images exhibit spin-echo-like behavior, such that spin isochromats at similar resonant frequencies show phase coherence at either 0° or 180° relative to the RF pulses at the time TR/2, the nominal TE in SSFP imaging (13). 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 by adjusting the center reference frequency, which in turn determines the directional location for phase coherence in the rotating frame (13). 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 (14). In this study, we demonstrate the feasibility of separating fat and water signals in SSFP imaging using the Dixon method in vivo at a high magnetic field (3.0 Tesla). We note that certain cautions should be used with this approach, and describe optimal off-resonance ranges using both theories and experimental results.

METHODS AND MATERIALS

Theories

The current technique 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 (13). The steady-state

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transverse magnetization immediately after the RF pulse, $M^*_x$ and $M^*_y$, can be expressed as a function of TR, $T_1$, $T_2$, flip angle $\alpha$, and the SSFP angle $\theta$ within one TR, given by (8):

$$M^*_x = M_0(1 - E_1)(E_2 \sin \alpha \sin \theta)/D$$  \hspace{1cm} [1]

$$M^*_y = M_0(1 - E_1)(1 - E_2 \cos \theta) \sin \alpha)/D$$  \hspace{1cm} [2]

with

$$D = (1 - E_1 \cos \alpha)(1 - E_2 \cos \theta)$$  \hspace{1cm} [3]

$$E_1 = e^{-TR/T_1}$$  \hspace{1cm} [4]

$$E_2 = e^{-TR/T_2}$$  \hspace{1cm} [5]

where $M_0$ is the magnetization at thermal equilibrium, and $\theta$ includes the effects of chemical shift and RF phasing. It can be shown that the transverse magnetization at TE = TR/2 shows phase coherence at 0° relative to the RF pulses for $4\pi n < \theta < (4n + 2)\pi$ in the rotating frame, or at 180° relative to the RF pulses for $4n\pi < \theta < 4(n + 2)\pi$, where $n$ is an arbitrary integer. Figure 1 shows the signal intensity and the phase angle relative to the RF pulses, plotted as a function of the off-resonance frequency for muscle (water) and fat protons, respectively, assuming 180° phase alternations for the RF excitation pulses (13). The calculations were performed for TR = 3.4 ms at 3.0 Tesla (the rationale for choosing TR = 3.4 ms is explained below). It is seen from Fig. 1 that in-phase and out-of-phase images at the chosen TR are both obtainable by appropriately adjusting the center frequency offset, if shimming can be performed satisfactorily (13). For example, an off-resonance of 0 to –120 Hz would lead to out-of-phase images, whereas an off-resonance of 20–130 Hz would result in in-phase images. This property justifies the use of the Dixon method for fat–water separation using SSFP at otherwise identical scanning parameters.

However, one should note that not all TRs are eligible for the proposed Dixon method. In particular, at TR equal to the inverse of the chemical shift (2.24 ms at 3.0 Tesla), it has been shown that the water and fat protons would always be out of phase in an SSFP image (15). In other words, in-phase images would not be obtainable. This is understood because a TR of 2.24 ms introduces a difference of $2\pi$ in the SSFP angles for water and fat. By the same token, at TR equal to an even multiple of 2.24 ms, the water and fat protons would always be in phase. On the other hand, if one selected a zero frequency offset for water at TR = 3.4 ms at 3.0 Tesla, the fat signal would be close to its minimum intensity, as shown in Fig. 1a. In this situation, since the exact “null point” for fat is very sensitive to the local magnetic field strength, the difficulty of obtaining homogeneous intensity for fat at this frequency offset would lead to imperfections in signal cancellation from in-phase and out-of-phase images. Fat–water separation would thus be nonideal. To address the issues of TR selection and heterogeneity in signal intensity, we performed the following analysis:

Equations [1]–[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 in units of Hertz for muscle (water) and fat protons, respectively, assuming 180° phase alternations for the RF excitation pulses. The calculations were performed with TR = 3.4 ms and TE = TR/2 at 3.0 Tesla, at a flip angle of 24° (the same parameters as used in the experiments). It can be seen that in-phase images (regions showing overlapped curves in b) and out-of-phase images (regions showing 180° separation in b) are both obtainable by carefully adjusting the off-resonance frequency, even using the same TE and TR values. This illustrates the feasibility of using the Dixon method for fat–water separation.
flat regions in Fig. 1a). For the remaining frequency offsets that provided fairly uniform signals for both water and fat, the phase angles of the two species were examined. The above process was repeated for TR = 2.0–7.0 ms. Thus, a graph was generated that 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 optimum TR for SSFP Dixon imaging, and was therefore chosen for the 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 were far from the null signal regions for both fat and water.

Image Acquisition

Abdominal imaging was performed on eight healthy adults (seven males and one female, 23–38 years old) who volunteered to participate in this study. Experiments were performed on a 3.0 Tesla MRI system (Siemens Trio, Erlangen, Germany). Transaxial SSFP images at about the kidney level were acquired using a 2D TrueFISP sequence. Transaxial SSFP images at 3.0 Tesla (flip angle 24°, 180° phase alternations for the excitation RF pulses) as a function of TR and center frequency offset. The abbreviations "ip" and "op" represent in-phase and out-of-phase behavior for muscle and fat, respectively. The stripe-like regions correspond to those that are not recommended for use in Dixon imaging because the signals from muscle or fat (or both) are close to zero, and hence are likely to cause imperfect signal cancellation or shimming difficulties. At TR equal to odd multiples of 2.24 ms (i.e., the inverse of the chemical shift frequency difference), the SSFP images would always show out-of-phase behavior, whereas at TR equal to even multiples of 2.24 ms, muscle and fat would always be in phase. The vertical dashed line corresponds to the experimental condition (TR = 3.4 ms, about halfway between 2.24 ms and 4.48 ms) used in this work. The different center frequency offsets yield half in-phase and half out-of-phase SSFP images, and thus are optimal for Dixon imaging.

RESULTS

Figure 2 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 that are not recommended for use in Dixon imaging because the signals from either muscle or fat (or both) are close to zero, and hence are likely to cause imperfect signal cancellation or shimming difficulties. From Fig. 2 it can be seen that at TRs equal to odd multiples of 2.24 ms (i.e., the inverse of the chemical shift frequency), the SSFP images would always show out-of-phase behavior, consistent with results from a previous report (15). In contrast, at TRs equal to even multiples of 2.24 ms, muscle and fat would always be in phase. Thus it becomes clear that the choice of TR = 3.4 ms (about halfway between 2.24 ms and 4.48 ms) 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. 2). Therefore, a TR of 3.4 ms was selected for all experiments performed in this study. Furthermore, at TR = 3.4 ms, the frequency offsets of +80 Hz and −80 Hz are optimal for in-phase and out-of-phase imaging, respectively, because the obtained images are relatively immune to intensity heterogeneity near the null signal points.

Figure 3a–e show the series of abdominal images from one male subject (27 years old) at different RF off-resonance frequencies (−80 Hz, −40 Hz, 0 Hz, +40 Hz, and +80 Hz). As the off-resonance frequency changes from −80 Hz to +80 Hz, one can observe from the boundaries of the kidneys that the images change from out-of-phase to in-phase in appearance. Of note, in the +40 Hz image (Fig. 3d), the right kidney demonstrates out-of-phase characteristics (long arrow), whereas the left kidney shows in-phase characteristics (short arrow). This is obviously due to shimming imperfections resulting in different effective off-resonance frequencies across a large FOV. In addition, a
dark band in the fat region can be seen between the two kidneys (open arrow), showing the presence of the null point for fat protons, consistent with the theoretical prediction shown in Fig. 1. The on-resonance image in Fig. 3c also shows an obvious dark band within the left-side subcutaneous fat. These images both represent situations in which fat protons are near the null points in Fig. 1 (\(n = 2\pi\), where \(n\) is an arbitrary integer).

Figure 4a and b show the water-only and fat-only images, respectively, obtained from the +80 Hz in-phase and the –80 Hz out-of-phase images in Fig. 3. Nearly complete fat suppression can be seen in Fig. 4a. Note that although the on-resonance image in Fig. 3c is also out-of-phase in characteristics, the presence of banding would result in incomplete fat cancellations if Fig. 3c were used along with Fig. 3e to form the water-only image (result not shown). This is in good agreement with our theoretical prediction from Fig. 2. Figure 4c shows a fat-suppressed image on the same slice location, acquired via one single fat-suppression RF pulse followed by a 2D SSFP readout with centric phase encoding (i.e., the manufacturer-supplied fat-suppression TrueFISP sequence). Note in particular the change of image contrast in Fig. 4c to proton-density weighted, compared with the \(T_2/T_1\) weighting in Fig. 4a, which provides much better contrast between the muscle and kidneys.

**DISCUSSIONS AND CONCLUSIONS**

We have presented a Dixon-based method for fat–water separation using in-phase and out-of-phase SSFP imaging. We 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 optimum TR and offset values for SSFP Dixon imaging. Unlike the Dixon method used in conventional gradient-echo imaging (14), SSFP Dixon imaging employs the concept of spin-echo-like phase coherence at \(T_2/2\) (13). This phase coherence is dependent on the SSFP angle, which is tunable via adjustments of the center reference frequency. One notices that for a wide range of SSFP angles, there are essentially only two orientations in which phase coherence occurs (i.e., 0° and 180°) relative to the RF pulses (Fig. 1). Consequently, the exact value of the off-resonance frequency chosen to form in-phase or out-of-phase images is not critically important, as long as the low-signal region can be effectively avoided (Fig. 2). This idea is supported by our experimental results, which indicate that nearly complete fat–water separation was achievable at ±80 Hz off-resonance. These off-resonance frequencies corresponded (Figs. 1 and 2) to situations in which both fat and water signal phases were relatively insensitive to slight changes in the SSFP angle due to shimming imperfections.
Fat suppression in SSFP imaging can be accomplished by several other approaches (5,9,15). The use of a frequency-selective RF pulse to achieve either fat suppression or water excitation (5) appears to be a straightforward technique for that purpose. However, since frequency-selective RF pulses generally have a long duration, on the order of several milliseconds (i.e., the inverse of the fat–water chemical shift), the employment of these RF pulses in every TR inevitably increases the minimum TR values substantially, from about 4–5 ms to 6–8 ms. The resulting increase in the total scan time is already on the same order (i.e., a factor of 2 increase) as that in SSFP Dixon imaging. In addition, increases of TR in SSFP imaging may hurt image quality by introducing banding artifacts, particularly at higher magnetic fields (e.g., 3.0 Tesla). At such fields, shimming is more difficult to perform than at lower fields because of strong susceptibility effects.

Hargreaves et al. (15) recently described a closely related approach that makes use of the off-of-phase nature for fat and water at a TR equal to the inverse of the chemical shift. With the background phase corrected, this method achieves fat–water separation in a single scan. A minor drawback of this approach is that the single-shot method can not perform separation in voxels that contain a partial volume mixture of different spectral species. In contrast, with the use of complex subtraction in SSFP Dixon imaging, as described in this study, one can achieve fat–water separation even in the presence of partial volume effects, at the expense of twice the scan time.

Compared with SSFP fat suppression using the algorithm proposed by Scheffler et al. (9), the Dixon-based method has the disadvantage of requiring a longer scan time (by a factor of 2) to obtain in-phase and out-of-phase images. Subject motion between successive scans could lead to imperfect fat cancellation due to image misregistration. Nevertheless, since the scan time is <1 s per slice, involuntary motion is expected to be minimal. The insensitivity of the technique to the exact value of the off-resonance frequency in obtaining in-phase or out-of-phase images also makes this method easy to use. In clinical applications where quantification of fat content is of diagnostic value (17,18), SSFP Dixon imaging may be an effective alternative for achieving fat–water separation relatively quickly.

In situations where more than two frequency components are present, such as imaging in breasts with silicone implants (19), it should be possible, by carefully selecting the off-resonance frequency, to obtain images that show, for example, in-phase behavior for water and silicone gel, and out-of-phase characteristics for fat/water and fat/silicone gel. Under such circumstances, the SSFP Dixon method may be useful for selectively isolating one frequency component (e.g., silicone gel) using only two acquisitions.

In conclusion, we have successfully demonstrated the feasibility of separating fat and water signals in SSFP imaging based on the Dixon approach. We analyzed the in-phase and out-of-phase behavior as a function of TR and center frequency offset. This method is directly applicable to systems equipped with a generic SSFP imaging sequence, with no need for advanced pulse programming, and potentially allows for the quantification of fat/water content even in the presence of partial volume effects. An investigation of this approach in terms of clinical applications is currently under way.

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9. Scheffler K, Hennig J. Magnetization preparation during the off-resonance frequency, to obtain images that show, for example, in-phase behavior for water and silicone gel, and out-of-phase characteristics for fat/water and fat/silicone gel. Under such circumstances, the SSFP Dixon method may be useful for selectively isolating one frequency component (e.g., silicone gel) using only two acquisitions.