Original Research

# Separation of Fat and Water in Fast Spin-Echo MR Imaging with the Three-Point Dixon Technique[1]

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**A method for suppressing fat in fast spin-echo imaging with the three-point Dixon technique is described. The method differs from the three-point Dixon method used in conventional spin-echo imaging in that the readout gradient instead of a radio-frequency pulse is shifted. This method preserves the Carr-Purcell-Meiboom-Gill nature of the fast spin-echo sequence and hence is less sensitive to magnetic field inhomogeneities and resonance frequency mistuning. As in the original three-point Dixon technique used in conventional spin-echo imaging, three acquisitions are required to estimate the field inhomogeneity and completely separate fat and water. The extra time required is not excessive considering that the fast spin-echo method is frequently applied with multiple signal acquisition. Also, this technique achieves an expected signal-to-noise ratio comparable to 2.67 signal acquisitions, which is approximately 94% of the signal-to-noise ratio obtained with three signal acquisitions. The method is demonstrated with applications to phantoms and a human volunteer.**

**Index terms:** Image processing • Phase imaging • Pulse sequences • Rapid imaging • Tissue suppression

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**Abbreviations:** FSE = fast spin echo, RF = radio frequency.

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FAT-SUPPRESSED T1-weighted magnetic resonance (MR) images are useful for diagnosing disease. Fat suppression in contrast agent–enhanced, T1-weighted images permits the reliable differentiation of tumor, subacute hemorrhage or cysts with high protein content, and lipomas. A variety of techniques have evolved for obtaining fat-suppressed images. The most common of these is selective saturation with spectrally selective pulses such as binomial or amplitude-modulated pulses with a resonance frequency centered on the fat resonance (1,2). When used in spin-echo sequences, this technique has the advantage of easy implementation and minimal increase in acquisition time. The disadvantage of selective saturation is that the fat is not always completely saturated.

Figure 1 is a fat-suppressed axial spin-echo image of the brain of a healthy volunteer. Note that the fat saturation is not uniform, since fat around the orbits and adjacent to the nasal sinus is still bright. Magnetic inhomogeneity in this region shifts the local resonance frequency enough so that the lipid protons are not affected by the spectral saturation pulse. Shimming of the magnetic field before acquisition and the use of test sequences to find the optimal offset frequency for the selective pulse can improve the uniformity of fat suppression. These techniques fail, however, to overcome local field inhomogeneities completely and add time to the total study.

An alternative to spectral saturation is use of the three-point Dixon technique (3,4), which collects three spin-echo images with the relative phase of fat and water shifted between $-\pi$, 0, and $+\pi$. These three pairs of images (magnitude and phase) can be recombined to provide unambiguous separation of fat and water even in the presence of $B_0$ field inhomogeneities. The disadvantage of the three-point Dixon method is the added time needed to produce a three-signal image. However, the resulting water-only and fat-only images have a signal-to-noise ratio equivalent to a 2.67-signal-average image. Additional advantages accrue from the availability of fat-only, water-only, and magnetic field maps—features not available from a fat-suppressed acquisition.

Fat suppression is also important in fast spin-echo (FSE) imaging. In many applications—such as imaging of the brain, spine, and knees—FSE imaging is being used in place of conventional spin-echo imaging. In these applications, fat suppression becomes as important as it is in conventional spin-echo imaging. In conventional spin-echo imaging, it is generally only important to achieve fat suppression on T1-weighted images, since on T2-weighted images the fat signal has decayed sufficiently so that it is not confused with the high signal intensity due to disease. On T2-weighted FSE images, fat remains bright because the rapid 180° pulses suppress the modulation of lipid protons that otherwise gives fat a short T2 (5–7). In fact, on T2-weighted FSE images, fat is unusually bright (8). For example, the contrast-to-noise ratio between fat and skeletal muscle for a single-section FSE sequence with a TR msec/TE msec of 2,500/90 and an echo train length of 11 was measured at 44. With the equivalent conventional sequence, the ratio was only 23. By imaging with only one section, the confounding effects of incidental magnetization transfer were minimized (9). This contrast-to-noise ratio will increase as FSE techniques with more radio-frequency (RF) pulses and larger bandwidths are used to further reduce the acquisition time. Thus, even with T2-weighted FSE sequences it is important to develop a reliable method for fat suppression. In this case, the advantage of the three-point Dixon technique in providing complete separation of fat and water even in the presence of field inhomogeneities will be important.

Methods for reducing the fat signal in FSE imaging have already been proposed (10). Shifting the position of the 90° pulse by $\Delta t = \pi/2\omega$, where $\omega$ is the fat-water frequency difference, puts the lipid protons out of phase with respect to the 180° pulses and thereby substantially reduces the fat signal. While achieving fat suppression without any increased acquisition time, this technique has the important disadvantage of defeating the beneficial Carr-Purcell-Meiboom-Gill (CPMG) character of the FSE sequence (11). In this case, all spins, regardless of their chemical origin, will vary in their effective T2, depending on their off-resonance frequency. In addition, the sensitivity of the technique to magnetic field inhomogeneities means that it will not succeed in all cases.

In the present application of the three-point Dixon technique, the readout gradient ($G_x$) was moved by $\pm t_0$, which is equal to $\pm 1/\omega$, or $\pm 2.2$ msec, to achieve a $\pm\pi$ phase shift between water and fat. The modifications to the FSE sequence needed to implement this technique are shown in Figure 2. With this method, the RF Hahn echo still occurs midway between the 180° pulses and the CPMG character of the FSE sequence is preserved. The gradient echo occurs at the center of the readout window and is displaced from the Hahn echo by $\pm t_0$. This change does not affect the magnitude of the image substantially, and the three complex images created can be treated as having equal magnitude but different phase.

## • MATERIALS AND METHODS

A prototype FSE sequence was provided to our institution by GE Medical Systems (Milwaukee, Wis) to run on a Signa 1.5-T whole-body imager. The sequence was modified to allow shifting of the readout gradient by an arbitrary amount. The data acquisition window and the phase-encoding gradients were also shifted by an equal amount to keep them aligned with the readout gradient. The readout dephasing gradient was not altered.

The modified sequence was used to image a phantom consisting of bottles of vegetable oil and water. T1-weighted images (600/20) were obtained with the head coil and with an echo train length of four. Phase and magnitude images were reconstructed for each acquisition. T1-weighted images (750/25) were also obtained through the orbits of a healthy volunteer, with an echo train length of four and one signal acquired per image. The total acquisition time for these 256 × 192 matrix images was 1.5 minutes.

Reconstruction of the fat- and water-only images was done on a Sun 4/370 workstation (Sun Microsystems, Mountain View, Calif). An algorithm closely following that outlined by Glover and Schneider (4) was used to unwrap phase shifts beyond $\pm\pi$ and to obtain clear separation of the fat and water phases. All operations were done on a pixel-by-pixel basis. The phase of the $\Delta t = 0$ image was subtracted from the $\pm t_0$ images to remove the constant phase offset

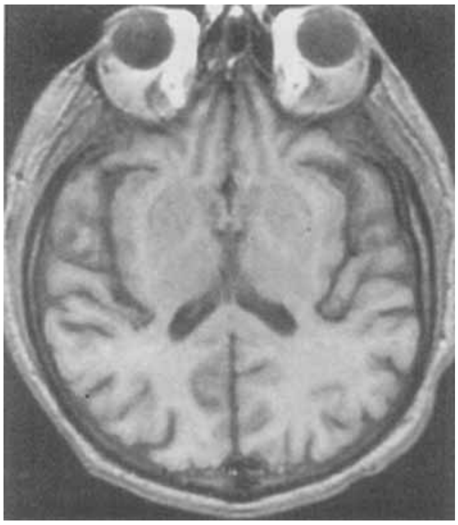


**Figure 1.** Axial fat-suppressed image of the brain of a healthy volunteer. Note that the fat in the orbits and adjacent to the nasal sinus is incompletely suppressed.

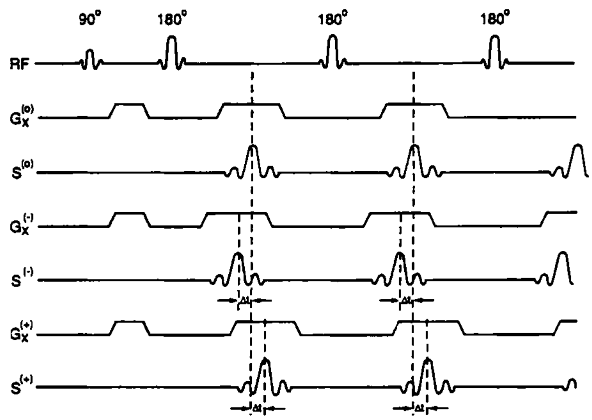



**Figure 2.** Modifications to the FSE sequence to implement the three-point Dixon technique. Shifting the readout gradients (G) by a time $\Delta t$ separates the Hahn (S) and gradient echoes by $\Delta t$.

that may arise from the electronics and the variation in the sensitivity of the receiver coil (12). The two resulting images are further subtracted, and any resulting phase aliasing is removed. When these two images are subtracted, the resultant image contains a map of the field inhomogeneity. This map can be used to correct the phase of one of the two intermediate images to get an unambiguous map of water and fat distributions. Calculated images were returned to an imager for display and filming.

## • RESULTS

The variation in phase of water and vegetable oil with a series of offsets is illustrated in Figure 3. The rate of phase change ($\Delta\phi/\Delta t$) is −209 Hz, which is appropriate for the frequency difference between fat and water. An independent measurement of the Larmor frequency of the vegetable oil protons was obtained by operating the imager in spectroscopy mode and observing the spectrum of the vegetable oil. With this technique, it was determined that $\omega_{fat}$ is equal to −200 Hz. Phase images of this phantom at three times ($\Delta t$ = −2,048 µsec, 0, +2,048 µsec) are shown in Figure 4a, 4c, and 4e, and the corresponding magnitude images are shown in Figure 4b, 4d, and 4f. Note that the phase of the oil varies greatly and that a portion of the oil experiences a phase wraparound for $+t_0$. Figure 5 shows the reconstructed fat- and water-only phantom images. Comparing the signal intensity of the reconstructed images with that of the original images, we determined that 99% of the water signal was correctly recovered and 88% of the oil signal was recovered. Less of the oil signal was recovered because the magnitude of the oil signal on the $\pm t_0$ images was reduced because of the destructive interference due to the different components in the oil spectrum (13).

The signal-to-noise ratio of the water in the reconstructed images was compared with that in the original image with a zero time shift. Because the signal intensity of the two images was equivalent, it was necessary only to estimate the standard deviation of the two signals to compare their signal-to-noise ratios. However, the signal intensity across the phantom was not homogeneous, and it was not possible to directly estimate the variation in standard deviation due to the reconstruction. Instead, four sets of the three images needed for water-fat separation were collected in a phantom consisting of bottles of vegetable oil and water. Water- and fat-only images were created from these four sets. Pairs of the water-only images were subtracted, and the standard de-

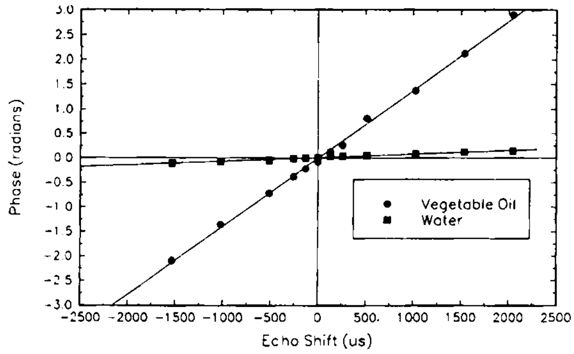



**Figure 3.** Image phase of samples of vegetable oil and doped water is plotted as a function of the offset time of the readout gradient. *us* = µsec.

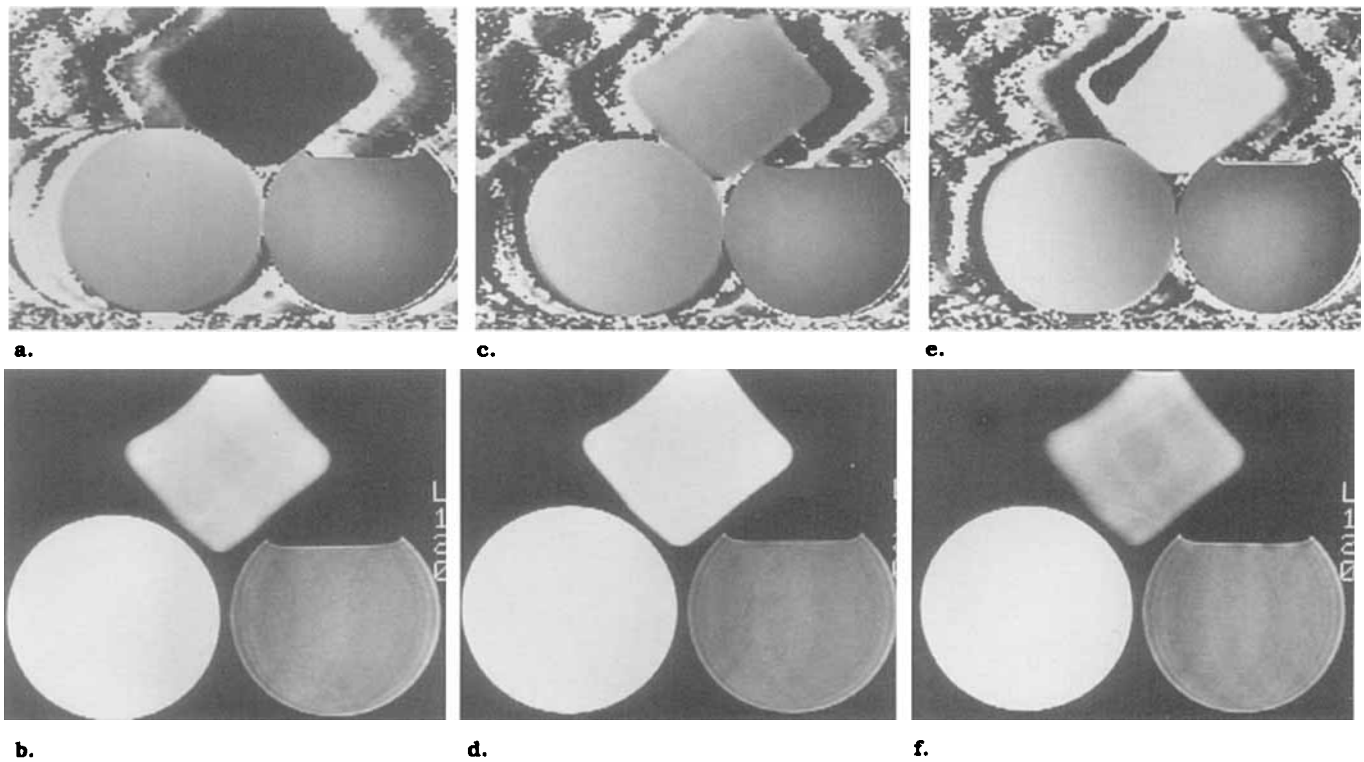



**Figure 4.** Phase (**a, c, e**) and magnitude (**b, d, f**) images of the water and vegetable oil phantom obtained with $\Delta t$ = −2,048 µsec (**a, b**), 0 (**c, d**), and +2,048 µsec (**e, f**). The square-shaped bottle contains the vegetable oil, and the two circular bottles contain water doped with different concentrations of copper sulfate.

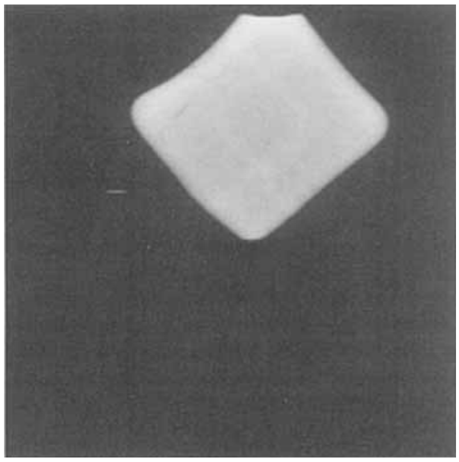
viation over a large area of the water phantom was calculated. The equivalent procedure was performed on the original, zero-time-shifted spin-echo images. The average ratio of the standard deviations of the two image types, $\sigma_{original}/\sigma_{reconstructed}$, was $1.58 \pm 0.13$, which is in agreement with the expected ratio, 2.67, or 1.63 (3).

The water- and fat-only images of the volunteer's head are shown in Figure 6. Note that the suppression of fat signal around the orbits and nasal sinus is improved over that in Figure 1. The ability of the three-point Dixon technique to overcome $B_0$ inhomogeneities is an important advantage relative to other fat suppression techniques. Some fat signal still remains in the water-only image and this is probably a result of the inability of the cubic function chosen to fit the surface of the inhomogeneity to adequately describe the complex variation in $B_0$. Better phase unwrapping methods could be applied to this technique to improve its performance without any increase in image acquisition time.

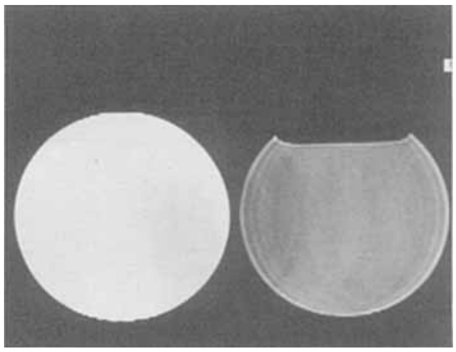
## • DISCUSSION

Suppression of the fat signal in FSE imaging is an important goal to prevent confusion of this signal with that from a lesion. As FSE techniques become more widely used in clinical practice, the need to incorporate fat suppression will correspondingly increase. The three-point Dixon technique for suppressing fat signal will have utility in many areas of MR imaging. Even though it requires the acquisition of three images, the fourfold decrease in imaging time achieved by using an FSE sequence with an echo train length of four more than offsets this deficiency. Considering that multiple-signal acquisition is frequently used in FSE imaging, the three acquisitions needed with this technique are not excessive.

The major disadvantage of this FSE technique is the reduced number of sections available in one acquisition pass. With a TR of 750 msec, only six sections were available per pass. Concatenating acquisitions to cover a greater region of interest is possible; however, the advantages of the technique relative to the three-point Dixon method in conventional spin-echo imaging diminish accordingly. The technique is most appropriately used in regions in which the anatomic areas are small, such as through the orbits or the spine. When higher-bandwidth FSE images are acquired with more closely spaced RF pulses, the need to reduce the unwanted high-intensity fat on T2-weighted images will also increase. This technique can be used to suppress fat signal on T2-weighted FSE images without the problem of a reduced number of sections due to the increased TR used to obtain these images. The technique does,



a.



b.

**Figure 5.** Fat-only (a) and water-only (b) images of the water and vegetable oil phantom in Figure 4.

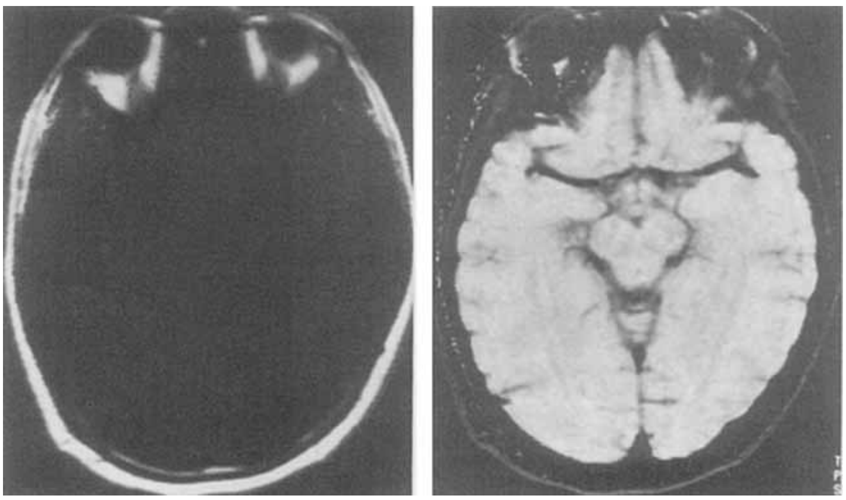


**Figure 6.** Fat-only (a) and water-only (b) images of the head of a healthy volunteer.

however, pose a limit on interecho spacing, since approximately 2 msec is required to shift the readout gradient to either side of the midpoint between the 180° RF pulses.

This acquisition technique is easily implemented, although more time is required for image reconstruction. This disadvantage can be seen as minor when one considers that there may be potential benefits of having separate fat- and water-only images compared with a single water-only image. For example, applying the technique to imaging silicone breast implants permits one to create silicone- and fat-only images, which may have value in the detection of breast implant rupture (14).

We have focused on acquiring FSE images with offsets of $-\pi$, 0, and $+\pi$. We note that it is also possible to produce fat- and water-only images by shifting the phase to 0, $+\pi$, and $2\pi$ (15). In that case, the minimum interecho time is increased. Generally, it is desirable to keep this time as short as possible to reduce T2 filtering of the image and to maximize the number of sections obtainable within a given TR. For these reasons, we have implemented only the ($-\pi$, 0, $+\pi$) phase-shift scheme.

In conclusion, the FSE version of the three-point Dixon technique can produce fat- and water-only T1- or T2-weighted images within a short acquisition time. Fat and water regions were reliably separated by using the decomposition program. It is anticipated that this technique will have greatest application in imaging of the spine and orbits because of the limited number of sections available per acquisition pass, or in the suppression of fat on T2-weighted FSE images, in which multiple echoes result in high-intensity fat. The technique has the advantages of providing improved fat suppression and separate fat- and water-only images. ●

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