Rapid Fat Suppression in MRI of the Breast with Short Binomial Pulses

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Purpose: To develop a faster method of fat suppression for use in dynamic contrast enhanced MRI of the breast.

Materials and Methods: A method of fast fat suppression is presented using spatially nonselective rapid binomial pulses. In contrast to conventional binomial frequency-selective pulses, these short pulses are applied without interpulse delay, allowing for very rapid spectrally selective excitation.

Results: Effective water excitation and fat suppression were achieved in breast MRI at 3.0 Tesla with total excitation time as low as 160 μsec, which is several times shorter than the excitation time of currently used fat suppression techniques. Rapid fat suppression comes at the expense of increased specific absorption rate (SAR) and mildly degraded quality of suppression. A flexible tradeoff of short imaging time vs. SAR can be made to optimize imaging speed for fat-suppressed breast MRI.

Conclusion: Rapid binomial pulses can be used for dynamic contrast enhanced breast MRI with excitation times significantly shorter than currently used fat suppression pulses. Shorter excitation time allows more rapid imaging, allowing greater temporal and spatial resolution for characterization of breast lesions.

Key Words: breast MRI; fat suppression; binomial pulses; dynamic contrast enhanced MRI; MRI pulse sequences

Technical Note

FAT SUPPRESSION is an important component of many MR imaging exams. In MR imaging of the breast, fat suppression is used to allow T2-weighted imaging of breast tissue and non-fatty lesions with fast spin-echo (FSE) sequences and to increase lesion conspicuity on dynamic pre- and postcontrast T1-weighted images (1). Both contrast-enhanced lesion morphology and temporal pattern of contrast enhancement are useful in the detection and characterization of breast cancer (2–4).

Because of the need for high spatial and temporal resolution, ongoing efforts have focused on increasing the speed of dynamic contrast enhanced breast imaging (5,6). The need for fat suppression has been a limiting factor in the reduction of repetition time (TR) in dynamic breast imaging. Conventional methods of fat suppression for breast imaging involve the use of long frequency selective soft pulses or hard binomial pulse trains. These pulses typically require durations equal to or greater than the inverse of the frequency difference separating water and fat. At 3.0 Tesla, this means a minimum pulse duration of approximately 2 msec. These frequency selective pulses frequently comprise a large fraction of the TR of a dynamic imaging sequence. Inversion recovery can also be used for fat suppression, with even longer resulting imaging time (5). Dixon techniques for formation of separate fat and water images have been applied to breast MRI in conditions of very poor B0 homogeneity (7–9), but these techniques require doubling or tripling of imaging time. Some investigators and equipment vendors have used intermittent fat saturation pulses which are played at the beginning of a short series of gradient recalled echo sequence repetitions rather than before each repetition, tolerating less than optimal fat suppression for the sake of faster imaging.

A type of binomial pulse called the “jump and return” (JR) has been proposed (10) as a means of spectrally selective excitation for solvent suppression in NMR spectroscopy. In this technique, a 90° pulse is followed by a period of precession τ and then a -90° pulse which returns the transverse magnetization of the on-resonance solvent spins to the z axis. Spectral selectivity of this sequence depends on the time interval τ between the 90° excitations, and this interval is chosen to give a 90° angle of precession to the desired signal component in order to maximize its transverse magnetization after the −90° flip-up. Another commonly used pulse known as the 1–1 binomial pulse (11) uses a 45°–τ –45° sequence with τ chosen such that the desired signal component precesses by 180° in the interval between the two pulses. For fat suppression at 3.0 T, the JR method would require an interpulse delay of about 500 μsec, leading to a total excitation time of around 600–700 μsec when the duration of realizable finite amplitude pulses is considered. The 1–1 binomial
The rotating delivery of excitation off-resonance (RODEO (12,13) technique has been proposed as a method of fast fat suppression and is similar in some respects to a 1−2−1 binomial pulse, requiring approximately 1.2 msec pulse duration for fat-water discrimination at 3 T.

A faster method of fat suppression with rapid binomial pulses was proposed (14) and demonstrated in musculoskeletal imaging. For this method it was recognized that binomial frequency selective excitation can be performed without waiting for the full interpulse delay necessary to achieve optimal signal from the desired imaging species. Thus this technique involved a rapid 90° excitation followed by a period of precession τ shorter than that of a binomial or JR pulse. A −90° excitation was then applied about an axis determined by the precession period τ and the off-resonance frequency of the signal to be nulled. Both pulses were modulated at the frequency of the desired signal component (e.g., water). The phase of the −90° pulse was chosen to tip the nulled component (e.g., fat) back to the Mx axis. In the published experiment, a 90° y pulse was followed by a precession interval τ sufficient to cause the precession angle of fat to equal 45°. A 90° pulse with phase offset of 135° was then applied to return the transverse magnetization of fat into the z axis while leaving residual transverse magnetization at the water frequency. An interpulse delay of 625 μsec was used on a 1.0 T system.

We demonstrate the use of a rapid binomial excitation pulse with no interpulse delay for very fast fat suppression in dynamic breast imaging. This pulse achieves water excitation with excellent fat suppression in minimum time. Results of breast MRI at 3.0 T are presented with combined soft tissue (water) excitation and fat suppression requiring total excitation time of as little as 160 μsec.

**MATERIALS AND METHODS**

The rapid binomial excitation pulse has an envelope shown in Fig. 1. A rapid spatially nonselective α flip is followed immediately by a −α flip about the same axis. These pulses are played with a modulation frequency (or radiofrequency (RF) carrier frequency) equal to the resonant frequency of fat. This eliminates the need for a special phase angle modulation of the second portion of the RF pulse as was originally proposed in Ref. 14.

Expressions for the magnetization created by this pulse can be derived by recognizing that the first half of the pulse amounts to a rotation of the initial longitudinal magnetization by an angle $θ = −τ \frac{ω^2 + \gamma^2 B^2}{(ω^2 + \gamma^2 B^2)^{3/2}}$ about the vector $γB\hat{x}$, where $ω$ is the off-resonance frequency, $γB$ is the nutation frequency due to the RF pulse, and $τ$ is the duration of the initial α flip that is applied about the $x$ axis. The sign of $θ$ is negative to denote left-handed rotation. The second half of the pulse is equivalent to a rotation of angle $θ$ about the vector $−γB\hat{x} + ω\hat{z}$. Given the condition $M^T \cdot [M^d, M^f, M^c] = [001]$ prior to the pulse, the magnetization at the end of the rapid binomial pulse is given by

![Figure 1. Rapid binomial pulse. The pulse consists of two subpulses, each of duration $τ$, with flip angles $α$ and $−α$.](image)

\[
M_x = \frac{2ωγB(1 - \cosθ)(ω^2\cosθ + γ^2B^2)}{(ω^2 + γ^2B^2)^{3/2}}
\]

\[
M_y = \frac{2ω^2γB\sinθ(1 - \cosθ)}{(ω^2 + γ^2B^2)^{3/2}}
\]

\[
M_z = \frac{ω^4 + 2ω^2γB^2\cosθ(2 - \cosθ) + γ^4B^4}{(ω^2 + γ^2B^2)^{3/2}}
\]

The magnetization of the transverse magnetization $M_{y0}$ with $M_{y0} = M_x + iM_y$ is plotted in Fig. 2 for a few values of flip angle $θ$. The phase of $M_{y0}$ can be disregarded, as it is constant between excitations and varies only with flip angle $θ$ and may therefore be assumed to vary slowly across the imaging volume. For water-only excitation in the breast, the pulse modulation frequency is set to the dominant fat resonance approximately 3.7 ppm below the water resonance, and water is off-resonance with respect to this pulse.

Examination of Fig. 2 shows that effective nulling of fat is sensitive to inhomogeneity of the main field $B_0$. Small variations in resonant frequency caused by $B_0$ inhomogeneity will cause some excitation of fat at some locations in the image volume. This sensitivity to $B_0$ variation is a price paid for very rapid excitation. Methods which use longer excitation periods are able to create wider spectral stop bands at the expense of increased imaging time.

**RESULTS**

In vivo studies were performed on a 3.0 T Siemens Trio imaging system using the multichannel breast coil available with the Siemens TIM coil package. Figure 3 shows representative images from a breast study performed with an RF spoiled three-dimensional gradient-recalled echo sequence utilizing a rapid binomial pulse. A 60°−60° pulse was used for water excitation and fat suppression with a total excitation duration of 160 μsec (i.e., $τ = 80$ μsec). The achieved flip angle at the water resonant frequency was approximately 13°. Figure 3
also shows images obtained with the same sequence without selective excitation, with the binomial pulse replaced by a hard pulse of equal duration and 12° flip angle. For this examination, meant to illustrate the limits of excitation speed, TR of 20 msec was required to avoid violation of SAR constraints.

Although some degradation of fat suppression is expected in regions of poor B₀ homogeneity, the quality of fat suppression obtained in this in vivo study with the rapid binomial pulse was quite uniform across a field of view encompassing both breasts as illustrated in Fig. 3, reflecting very little variation in B₀ across this volume.

A second in vivo study shown in Fig. 4 demonstrates more practical parameters for routine breast imaging. To reduce SAR, the excitation pulse length was extended to 360 μsec. To achieve a 13° flip angle of water with this pulse length, a flip angle of 25° was used for the α - -α excitation. This choice of pulse length and flip angle reduced SAR sufficiently to allow a 3.7 msec TR. Imaging was performed over a 17 cm × 14.6 cm × 14.6 cm field of view (FOV) with resolution of 1.1 mm × 1.1 mm in the sagittal plane, with 2.7 mm through-plane resolution. Total imaging time was about 30 seconds. In this study, effects of B₀ inhomogeneity were visible, with some non-uniformity of fat suppression as illustrated in Fig. 4.

DISCUSSION

Our most rapid implementation of the rapid binomial fat suppression pulse is based on a pulse length of 160 μsec. Figure 2. Magnitude of transverse magnetization produced by binomial pulse shown in Fig. 1 as function of flip angle α and off-resonance precession angle ω₀, obtained from Eq. [1]. For a 160 μsec pulse at 3.0 T, τ = 80 μsec and ω₀ is about 28° for water if excitation frequency is set to the major fat peak 3.7 ppm from water. For a 360 μsec pulse at 3.0 T, ω₀ is about 62°.

Figure 3. a,c: Sagittal images from an RF-spoiled 3D GRE study using 60° - -60° rapid binomial pulses for water-selective excitation, with total excitation duration of 160 μsec (τ = 80 μsec), demonstrating limits of excitation speed. Effective water flip angle was 13°. The center of the left breast is shown in (a). The far lateral right breast is shown in (c). Images are representative of the quality of fat suppression throughout the imaging volume. Because of SAR constraints, TR for this sequence was increased to 20 msec. b,d: Corresponding images from the same sequence with the water selective excitation replaced by a nonselective hard pulse of duration 160 μsec with flip angle 13°.
selective hard pulse excitation with duration 360 sec and flip angle 13°.

**Rapid Fat Suppression for Breast MRI**

Representative of quality of fat suppression throughout the entire imaging volume. The center of the left breast is shown in (a). The far lateral right breast is shown in (c). Images are representative of quality of fat suppression throughout the imaging volume. b,d: Corresponding images with non-selective hard pulse excitation with duration 360 μsec and flip angle 13°.

μsec, since 80 μsec is the shortest pulse width possible on our scanner for a 60° flip angle. In comparison, standard 1–1 binomial excitation would require about 1.2 msec, while the JR sequence would require about 700 μsecond. Even faster implementation is possible with our method if flip angles less than 60° are used. Lower binomial pulse flip angles and shorter pulse duration give unchanged suppression of fat but lower effective water flip angles. For instance, a 160 μsec 60° –60° pulse achieves a water flip angle of 13°, while a shorter 80 μsec 30° –30° pulse would achieve a water flip angle of only 3.5°.

The implementation of the fast binomial sequence is unchanged for 1.5 T or other field strengths, but the effective water flip angle for a given pulse duration and intensity decreases as field strength decreases. This can be seen with reference to Fig. 2, recognizing that change in field strength from 3.0 to 1.5 T causes a reduction in resonant frequency difference of fat and water from about 480 Hz to about 240 Hz, thus scaling the horizontal axis of Fig. 2 by a factor of one-half.

Since the quality of fat suppression with rapid binomial pulses degrades rapidly with variations in B0 as illustrated in Fig. 2, good shimming is essential for use of this technique. The in vivo studies shown in Figs. 3 and 4 were performed after standard volumetric shimming in the automatic prescan calibration of our imaging system. This sequence has so far been applied to only a small number of volunteers, but in this group acceptable fat suppression has been seen across the entire imaging volume.

Because the fast binomial technique employs two rapid α excitations to achieve selective water excitation with an effective water flip angle less than α, its SAR is increased in comparison to conventional gradient-recalled echo imaging. If SAR reduction is necessary, this may be achieved by decreasing the flip angle α of the rapid pulses and/or by increasing their length. Since the effective water flip angle varies approximately linearly with the angle of precession ωT as illustrated in Fig. 2, increasing pulse length leads to dramatic SAR reduction for a given effective water flip angle. For example, the 160 μsec 60° –60° sequence used in the study shown in Fig. 3 achieves an effective water flip angle of 13°. The 360 μsec excitation used for the study shown in Fig. 4 requires a flip angle of only 25° to achieve the same 13° water flip angle, thus resulting in a reduction in SAR of 92%. The tradeoff between excitation length and SAR is illustrated in Fig. 5 for several values of effective water flip angle. An optimal value may be found for each imaging situation which minimizes excitation time while maintaining SAR limits.

Our method is implemented with short RF pulses which are not spatially selective. Thus it is suited to three-dimensional imaging scenarios where the imaged volume can be limited by the use of surface coils or other coils having limited sensitive volume. A similar implementation could be performed using shaped α pulses with slice selection gradients, at the expense of increased pulse duration. If the shaped pulse lengths are extended to a duration of about 1 msec each, the excitation becomes similar to a conventional slice-selective fat/water selective 1–1 binomial excitation pulse for 3 T.

Lack of spatial selectivity is not a major drawback in dynamic imaging of the breast. T1-weighted pre- and postcontrast imaging is most efficiently performed with 3D sequences. Patients are imaged with dedicated breast coils. The configuration of commercially available breast coils has the patient lying prone on a coil superstructure, with the breasts dangling away from the body into the sensitive volume of the bilateral coil elements. The frequency direction, in which field of view is limited by bandpass filtering of the analog signal, is chosen anterior-posterior to eliminate cardiac motion artifact that would otherwise overlie images of the left
breast. The field of view in the superior–inferior and right–left directions need be only large enough to include the breasts. Aliasing from adjacent structures is avoided because the breasts are hanging away from the body, surrounded only by air. The limited extent of the sensitive volume of the breast coil eliminates aliasing from more distant body parts. Thus the only inefficiency of spatially nonselective excitation relative to conventional slab-selective excitation for 3D dynamic imaging of the breasts is the inclusion of the air-filled space between the breasts in the imaging field of view, which results in some increase in scan time. The in vivo studies shown in Figs. 3 and 4, performed with spatially nonselective excitation, demonstrate that aliasing is not a serious problem.

The rapid binomial pulse method of fat suppression is not sensitive to $B_1$ inhomogeneity, as the effective excitation at the fat resonant frequency is zero regardless of the value of flip angle $\alpha$. $B_1$ inhomogeneity causes variation in the magnitude of water excitation, but not degradation of fat suppression.

In conclusion, we have applied a rapid binomial method of selective water excitation and fat suppression to breast imaging to achieve good fat suppression and water excitation with pulse lengths much shorter than conventional fat suppression methods currently used in breast MRI. Imaging speed is of paramount importance in dynamic contrast enhanced breast MRI. In-vivo breast imaging experiments at 3.0 T have shown good suppression throughout an imaging volume encompassing both breasts with total water-only excitation time as short as 160 $\mu$sec, compared to 700–1200 $\mu$sec excitation time necessary for conventional fat suppression pulses. Uniformity of fat suppression may be slightly sacrificed in exchange for imaging speed. This technique has high SAR at very short excitation durations, but flexible tradeoff of imaging speed with SAR is possible, with dramatic SAR reduction for small increase in pulse length. This technique allows rapid fat suppression for 3D dynamic imaging and has the potential to dramatically reduce imaging time for dynamic breast MRI. Reduced imaging time results in greater spatial and temporal resolution, which may improve the accuracy of lesion characterization.

REFERENCES