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Water Excitation as an Alternative to Fat Saturation in MR Imaging: Preliminary Results in Musculoskeletal Imaging[1]

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Abbreviations:
CNR = contrast-to-noise ratio
ROI = region of interest
SE = spin echo
SNR = signal-to-noise ratio
TR = repetition time

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PURPOSE: To compare fat suppression methods by using spectrally selective fat saturation and section-selective water excitation in standard magnetic resonance (MR) imaging sequences used in day-to-day musculoskeletal practice.

MATERIALS AND METHODS: Eighty-three patients underwent MR examination with a 1.5-T system. The two methods were compared by using three common sequences: T1-weighted spin-echo (SE) imaging performed after contrast material injection (n = 24), intermediate-weighted fast SE (n = 36) imaging, and T2-weighted fast SE (n = 36) imaging. Acquisition times of the sequences and signal-to-noise and contrast-to-noise ratios of bone, muscle, fat, and water for the two methods were compared quantitatively. Images were then qualitatively reviewed by two radiologists who were blinded to the type of fat suppression used. Image quality was scored according to four criteria (homogeneity of fat suppression, susceptibility and foldover artifacts, conspicuousness of lesion, and overall image quality) by using a five-point scale (0, bad; 1, poor; 2, fair; 3, good; and 4, excellent). A paired Student t test was used to compare the quantitative data, and a nonparametric paired-data Wilcoxon signed rank test was used for qualitative analysis.

RESULTS: Water excitation allowed a substantial decrease in acquisition time (by up to 50%) for T1-weighted sequences. Quantitative measurements revealed a greater signal-to-noise ratio ($P < .01$) with water excitation for all three sequences, whereas the contrast-to-noise ratio was greater with water excitation only in intermediate-weighted sequences ($P < .01$). Qualitatively, water excitation proved statistically better than or equal to fat saturation for all criteria in all imaging sequences ($P < .05$). Mean scores of overall image quality ranged between 2.5 and 3.0 for fat saturation and 3.4 and 3.7 for water excitation, respectively ($P < .05$).

CONCLUSION: Section-selective water excitation is faster than conventional fat saturation and produces images of better quality.

Fat suppression is a fundamental technique in routine musculoskeletal magnetic resonance (MR) imaging that is used for three main purposes: *(a)* to emphasize water sensitivity when used in conjunction with intermediate- and T2-weighted fast spin-echo (SE) sequences, *(b)* to suppress the signal from normal adipose tissue to reduce chemical shift artifacts or to better visualize uptake of contrast material (eg, gadolinium-based material), and *(c)* to improve dynamic range in water-containing structures such as cartilage when used in conjunction with T1-weighted sequences.

The most widely used methods of fat suppression in musculoskeletal imaging are frequency-selective fat saturation and short inversion time inversion-recovery, or STIR. Both methods have disadvantages (1). Fat saturation is very sensitive to magnetic field variation due to tissue inhomogeneity or magnetic susceptibility. Moreover, the time required to apply the spectrally selective radio-frequency pulse (fat-saturation pulse) can substantially increase the imaging time in T1-weighted sequences. Inversion-recovery images in general have a lower signal-to-noise ratio (SNR) than do comparable fat-saturated T1- and T2-weighted images (1). In addition, fewer sections are obtained with STIR sequences than with fat-saturated sequences because of the time required to apply the inversion pulse. Lastly, the use of an inversion pulse suppresses all tissues with a short T1, thus explaining why gadolinium-based contrast material cannot be used with this imaging method (2).

An alternative to fat suppression methods—water excitation by means of a spectral spatial pulse—has been developed (3–14). With this technique, only water is excited by using section-selective composite pulses, while lipid spins are left in equilibrium, thereby producing no signal. These pulses have already been integrated into gradient-echo sequences for experimental studies (5,6,11,12), but, to our knowledge, this method has not been applied in standard SE sequences in previous clincial studies, particularly in musculoskeletal applications. The aim of this study was to compare fat suppression methods by using fat saturation and water excitation with spectral spatial pulses in standard sequences (ie, T1-weighted SE, intermediate-weighted, and T2-weighted fast SE sequences) used in day-to-day musculoskeletal MR imaging practice.

MATERIALS AND METHODS

Population

This was a prospective study that included 83 consecutive patients (47 male and 36 female patients; age range, 15–74 years; mean age, 42 years) who presented with a clinical history of musculoskeletal disease and were referred to our institution from March to November 2000 for MR examination. MR images of the shoulder (n = 16), elbow (n = 5), wrist (n = 7), hip (n = 12), knee (n = 28), ankle (n = 12), and soft tissues (n = 3) were obtained.

MR imaging was performed with the informed consent of the patients. Investigational review board approval was not required by the institution, since a standard imaging protocol was used. We received a waiver from our institutional review board for use of additional sequences.

Imaging Protocols

Imaging was performed with a 1.5-T MR imager (Gyroscan; Philips Medical Systems, Best, the Netherlands), with specific coils dedicated to the different joints: a circular surface coil for the shoulder and small joints, a four-element phased-array coil for the hip and soft tissues, and a volumetric quadrature coil for the knee and ankle.

Within the standard joint-specific imaging protocols, each fat-suppressed T1-weighted, intermediate-weighted, and/or T2-weighted sequence performed with a fat-saturated prepulse was systematically duplicated with spectral spatial pulses for water excitation with strictly identical parameters (repetition time [TR], echo time, number of signals acquired, field of view, and matrix). The matrix size was 256 × 256 for all sequences. The field of view was adjusted depending on the joint (from 90 to 420 mm). For all examinations, section thickness of fat-suppressed images was fixed at 5.7 mm because of software limitations on our MR imager at the time the study started.

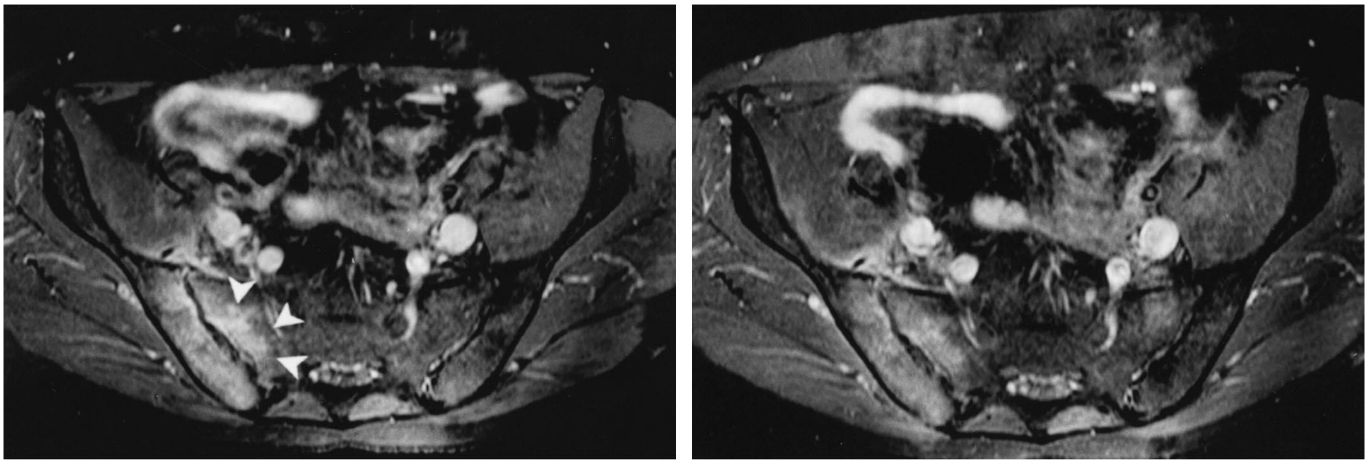
The comparison of the two methods of fat suppression was based on 24 T1-weighted SE 425–575/14–17 (TR msec/echo time msec) images obtained after injection of gadoterate meglumine (Dotarem; Guerbet, Roissy, France) (intravenously, 0.2 mL/kg [n = 21]; or intraarticularly, 1 mL diluted in 250 mL of saline for a total of 3 to 10 mL of this gadolinium compound, depending on the joint [n = 3]), 36 T2-weighted fast SE 2,000–2,315/60–80 images with an echo train length of seven, and 36 intermediate-weighted fast SE 2,000–2,200/14–17 images with an echo train length of five. For T1-weighted images obtained after injection of contrast material, fat-saturated acquisition was performed first, after a 10-minute delay following injection. Paired data from 96 images obtained in 83 patients were finally available.

Spectral spatial pulses are composite pulses in which the number, type, and amplitude of individual elements and the time interval between pulses determine their selectivity in frequency (7). The most commonly used spectral spatial pulses are composite pulses comprising standard section-selective pulses, in which amplitudes are given by means of binomial coefficients. Two types of composite pulses can be used routinely: a four-element composite pulse with a 1:3:3:1 amplitude ratio (11.25°:33.75°:33.75°:11.25°) and a three-element composite pulse with a 1:2:1 amplitude ratio (22.45°:45.00°:22.45°). In our study, we systematically used 1:3:3:1 composite pulses. Since both types of composite pulses were available, however, we included 1:2:1 composite pulses in addition to 1:3:3:1 composite pulses in 20 patients to evaluate and compare their influence on the images. This 20-patient subpopulation included 10 men and 10 women (age range, 28–70 years; mean age, 45 years) referred to our institution for MR examination of the wrist (n = 1), hip (n = 4), knee (n = 10), and ankle (n = 5). The sequences used were gadolinium-enhanced T1-weighted SE (n = 6), intermediate-weighted fast SE (n = 8), and T2-weighted fast SE (n = 6) sequences. Parameters of sequences were the same as those previously described.

Data Analysis

A quantitative analysis of both sets of fat-suppressed images (fat-saturated and water-excited) was performed. Acquisition times for the different sequences (T1-weighted SE, intermediate-weighted fast SE, and T2-weighted fast SE) with both types of fat suppression were first compared. By using a workstation (Easyvision; Philips Medical Systems), the same person (E.D.) placed regions of interest (ROIs) on the different tissues of the joint (bone marrow, muscle, fatty soft tissue, and liquid) on a selected image. The ROI measured between 150 and 200 mm^2, except for when placed on liquid, where ROI size depended on the amount of liquid present in the joint. For a given joint, the ROIs were identical and were placed at the same locations for all patients on all images analyzed. For both methods of fat suppression, the SNR and contrast-to-noise ratio (CNR) of the selected tissues were evaluated. The normalization to the noise was calculated by using the following formula: S/N, where S corresponds to the signal intensity of the tissues and N corresponds to the SD of the noise (15, 16). The SD of the noise was obtained by placing an ROI in a background area of the image that was free of signal or motion artifacts. The CNRs between bone marrow and muscle, bone marrow and liquid, muscle and fatty soft tissues, and muscle and liquid were calculated by using the following formula: $(S1 - S2)/N$, where $S1$ and $S2$ correspond to the signal intensity of the structures that are being compared and N corresponds to the corrected SD of the noise.

A qualitative analysis was then performed. Paired images from the two methods of fat suppression were retrospectively reviewed at separate sittings by two musculoskeletal radiologists (O.H., M.M.) who were blinded to the type of fat suppression and to the results of the quantitative analysis. The two observers



a. b.

Figure 1. Transverse gadolinium-enhanced T1-weighted SE 450/17 MR images obtained in a 36-year-old man suspected of having sacroiliitis on the right side. Bone marrow edema (arrowheads in **a**) related to inflammation of the right side of the sacroiliac joint is more pronounced with water excitation by means of **(a)** spectral spatial pulse with an acquisition time that is half that of **(b)** the frequency-selective fat saturation pulse (2 minutes 43 seconds vs 5 minutes 27 seconds). Fat-saturated acquisition was performed first, after a 10-minute delay following injection of contrast material.

TABLE 1
Signal Intensity Normalized to the Noise (SNR) of the Different Tissues in Intermediate- and T2-weighted Sequences with Both Methods of Fat Suppression

	Intermediate-weighted Fast SE		T2-weighted Fast SE	
Tissue	Fat Saturation	Water Excitation	Fat Saturation	Water Excitation
Bone marrow	41.0 ± 15.8	70.1 ± 11.5*	11.5 ± 6.5	18.0 ± 7.4
Muscle	111.3 ± 35.8	175.7 ± 23.7*	27.7 ± 8.1	33.9 ± 9.7
Liquid	232.5 ± 62.1	315.0 ± 46.1*	126.2 ± 47.6	171.7 ± 42.5*
Fatty soft tissue	62.9 ± 22.9	96.3 ± 19.2*	15.5 ± 4.7	23.7 ± 6.4*

Note.—Data are mean SNR ± SD. T1-weighted sequences are not shown because the difference between fat saturation and water excitation was only significant for muscle.
* Significant difference ($P < .05$) between fat saturation and water excitation.

separately reviewed the images on the workstation previously described. The images, containing no written data, were evaluated by using a five-point scale (0, bad; 1, poor; 2, fair; 3, good; and 4, excellent) applied on the basis of four criteria: homogeneity of fat suppression, presence of artifacts, conspicuousness of lesion (when present), and overall image quality. Homogeneity of fat suppression was assessed according to the strong and uniform suppression of all fatty tissues and the absence of either artifactual suppression or attenuation of tissues other than fat. For artifact evaluation, the type of artifact (ie, geometric distortion [metallic artifact] or foldover) was specified. Motion artifacts were not considered, since they are more dependent on the patient than on the sequence or the parameters used. The conspicuousness of the lesion was defined according to three criteria: visibility, margination, and extent. Overall image quality was based on the subjective appreciation of the SNR and CNR of the different tissues, the homogeneity of fat suppression, and the presence of artifacts.

The same quantitative and qualitative analyses were performed to compare the two types of binomial spectral spatial pulses (1:2:1 and 1:3:3:1) in the selected 20-patient subpopulation.

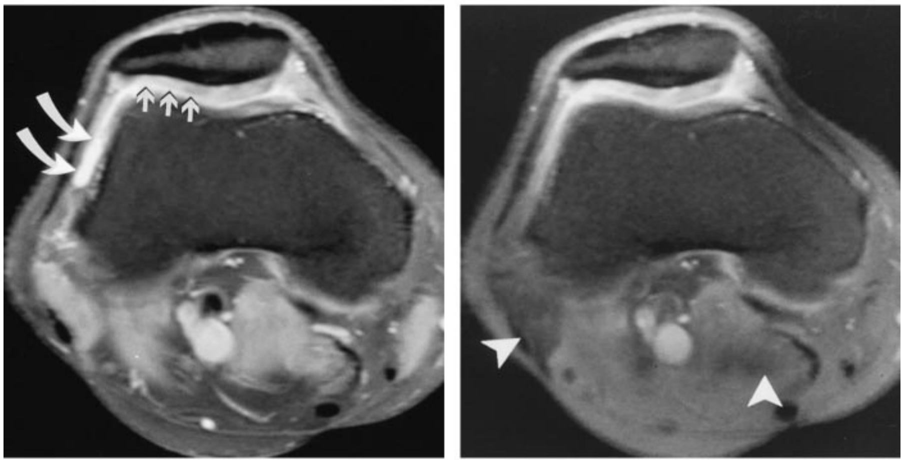
Statistical Analysis

A paired Student *t* test was used to compare the quantitative (SNR and CNR) data obtained with the two methods of fat suppression. Only *P* values of less than .05 were considered to indicate a significant difference. For qualitative analysis, a nonparametric paired-data Wilcoxon signed rank test was used, with significance defined as a *P* value of less than .05. Interobserver reproducibility for qualitative data was assessed by using the κ statistic for categoric parameters. A κ statistic of less than 0.20 represented a poor level of interobserver agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, good agreement; and 0.81–1.00, excellent agreement (17).

RESULTS

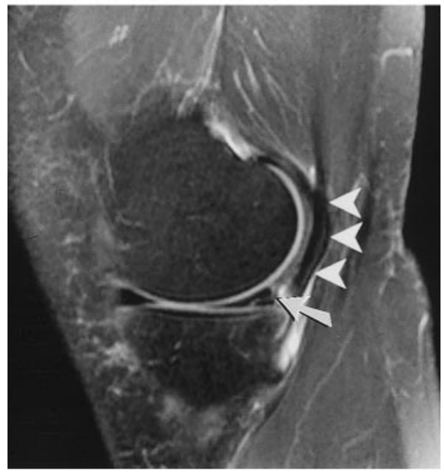
Type of Lesions

A total of 85 lesions were detected in 72 patients. No lesions were found in the other 11 patients. Twenty-one lesions involved the shoulder (partial or complete rotator cuff tears [n = 10], lesions of the superior labrum from anterior to posterior [n = 3], or subacromial bursitis [n = 8]), three involved the elbow (medial or lateral epicondylitis [n = 3]), five involved the wrist (Kienböck disease [n = 2]

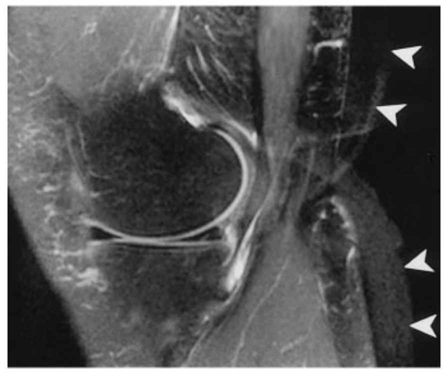


a. b.

Figure 2. Transverse intermediate-weighted fast SE 2,200/17 MR images of the knee in a 42-year-old man with recurrent knee pain. Images were obtained with water excitation by means of **(a)** spectral spatial pulse and **(b)** frequency-selective fat-saturation pulse. SNRs and CNRs are significantly greater with water excitation. This is partly due to artifactual attenuation of the muscle signal with fat saturation, particularly the biceps femoris and the gastrocnemius medial head (arrowheads). The signal intensity of the liquid (large arrows) is also much greater with water excitation. The heterogeneity of the cartilage, which is related to chondropathy, is better characterized on the image obtained with water excitation, with a better delineation of the cartilage surface of the lateral facette (small arrows).



a.



b.

Figure 3. Sagittal T2-weighted fast SE 2,000/80 MR images of the knee in a 28-year-old man with posteromedial knee pain who was suspected of having a meniscal tear. Images were obtained with water excitation by means of **(a)** spectral spatial pulse and **(b)** frequency-selective fat-saturation pulse. The meniscal tear of the posterior horn of the medial meniscus (arrow in **a**) is visible with both methods of fat suppression but is more conspicuous with water excitation (for both margination and extent). Fat suppression is also more homogeneous with water excitation and is particularly noticeable at the level of the semimembranous tendon (arrowheads in **a**). Foldover artifacts (arrowheads in **b**) are more intrusive on fat-saturated images.

or interosseous ligament tears [n = 3]), eight involved the pelvic region (avascular necrosis of the femoral head [n = 4], transient osteoporosis of the femoral head [n = 3], or sacroiliitis [n = 1]), 35 involved the knee (meniscal tears [n = 17], partial or complete anterior cruciate ligament tears [n = 15], or meniscal cysts [n = 3]), 10 involved the ankle (lateral collateral ligament tears [n = 3], tendon injuries [n = 4], or osteochondral lesions [n = 3]), and three involved the soft tissues (lipoma [n = 2] or histiocytofibrosarcoma [n = 1]).

Acquisition Time

There was a 50% decrease in total acquisition time of T1-weighted sequences after injection of contrast material with the water excitation method when compared with the fat saturation method in all patients (24 of 24) (Fig 1). Acquisition times ranged from 4 minutes 6 seconds to 6 minutes, 50 seconds with fat saturation pulses (mean, 4 minutes 38 seconds) and from 2 minutes 3 seconds to 3 minutes 25 seconds with spectral spatial pulses (mean, 2 minutes 19 seconds). No difference in acquisition time was noted for sequences with long TRs (intermediate- and T2-weighted sequences).

Analysis of SNR

Data from quantitative analyses are summarized in Table 1.

The SNR was significantly higher with water excitation than with fat saturation on intermediate-weighted fast SE images for all structures (bone marrow, muscle, fatty soft tissue, and liquid) ($P < .01$) (Fig 2). On T2-weighted fast SE images, the SNR of both liquid and fatty soft tissues was significantly higher with water excitation ($P < .05$). On gadolinium-enhanced T1-weighted images, only the SNR of muscle was significantly higher with water excitation ($P < .05$). In none of the different tissues was the SNR worse with water excitation than with fat saturation.

Analysis of CNR

Data from quantitative analyses are summarized in Table 2.

On intermediate-weighted fast SE images, the CNRs between bone marrow and muscle, bone marrow and liquid, muscle and liquid, and muscle and fatty soft tissue were statistically better with water excitation than with fat saturation ($P < .01$) (Fig 2). On T2-weighted images, the CNRs between bone marrow and liquid and muscle and liquid were significantly higher with water excitation, reflecting a higher SNR of liquid ($P < .01$). On gadolinium-enhanced T1-weighted images, there was no statistically significant difference in CNR of the different tissues between methods ($P = .65$).

Qualitative Analysis

Results are summarized in Table 3.

Water excitation proved to be statistically better than or equal to fat saturation for all criteria in all imaging sequences. The coefficients (κ statistics) of interrater agreement ranged from 0.78 to 0.82, indicating a high level of agreement.

Homogeneity of fat suppression was considered significantly better with water excitation on intermediate-weighted fast SE and T2-weighted fast SE images ($P <$ .01) (Fig 3), whereas no difference was

TABLE 2
CNRs between Different Tissues in Intermediate- and T2-weighted Sequences with Both Methods of Fat Suppression

Tissue	Intermediate-weighted Fast SE		T2-weighted Fast SE	
	Fat Saturation	Water Excitation	Fat Saturation	Water Excitation
Muscle and bone marrow	70.3 ± 25.6	105.6 ± 19.9*	16.2 ± 8.3	15.9 ± 9.5
Liquid and bone marrow	191.5 ± 53.9	244.9 ± 41.3*	114.7 ± 45.9	153.7 ± 41.0*
Liquid and muscle	121.2 ± 49.5	139.3 ± 37.7	98.5 ± 44.6	137.8 ± 34.3*
Muscle and fatty soft tissue	48.3 ± 28.3	79.3 ± 21.6*	12.2 ± 8.5	10.3 ± 7.9

Note.—Data are mean CNR ± SD.
* Significant difference ($P < .05$) between fat saturation and water excitation.

TABLE 3
Qualitative Comparison between Both Methods of Fat Suppression for T1-weighted SE, Intermediate-weighted, and T2-weighted Fast SE Images

Feature	T1-weighted		Intermediate-weighted		T2-weighted	
	Fat Saturation	Water Excitation	Fat Saturation	Water Excitation	Fat Saturation	Water Excitation
Homogeneity of fat suppression	3.2 ± 0.9	3.2 ± 0.6	2.9 ± 0.8	3.7 ± 0.4*	2.6 ± 0.8	3.1 ± 0.8*
Presence of artifacts	3.2 ± 1.1	3.4 ± 0.8	3.6 ± 0.7	3.6 ± 0.4	2.2 ± 1.0	3.2 ± 0.9*
Conspicuousness of lesion						
Visibility	3.1 ± 0.9	3.5 ± 0.7*	3.6 ± 0.8	3.7 ± 0.4	2.8 ± 0.7	3.3 ± 0.5*
Margination	2.9 ± 0.6	3.5 ± 0.5*	3.1 ± 0.5	3.7 ± 0.5*	2.4 ± 0.8	3.0 ± 0.7*
Extent	3.1 ± 0.9	3.2 ± 0.7	3.5 ± 0.6	3.6 ± 0.4	2.9 ± 0.6	3.1 ± 0.6
Overall image quality	2.9 ± 0.8	3.5 ± 0.7*	3.0 ± 0.7	3.7 ± 0.5*	2.5 ± 0.8	3.4 ± 0.8*

Note.—Numbers are mean values ± SDs. Comparison was based on a five-point scale (0, bad; 1, poor; 2, fair; 3, good; and 4, excellent).
* Significant difference ($P < .05$) between fat saturation and water excitation.

noted on T1-weighted SE images (P = .96).

Artifacts were considered significantly less intrusive with water excitation on T2-weighted fast SE images ($P < .001$) (Fig 3), whereas no difference was noted between the two methods on T1-weighted SE and intermediate-weighted fast SE images (P = .08 and P = .78, respectively). Metallic implant artifacts, however, when present, were considered significantly less intrusive with water excitation (Fig 4).

As for the conspicuousness of lesions, all lesions were visible on images obtained with both water excitation and fat saturation. Lesion visibility was significantly better with water excitation on T1-weighted SE and T2-weighted fast SE images (P = .02 and $P < .01$, respectively) (Fig 3), whereas no difference was noted on intermediate-weighted images (P = .56). The margination of the lesion was considered better with water excitation for all sequences ($P < .01$). No difference was noted between the two methods for the extent of the lesion.

Overall image quality was significantly better with water excitation than with fat saturation for all three sequences ($P < .01$).

Comparison between 1:2:1 and 1:3:3:1 Spectral Spatial Pulses

The quantitative analysis of both SNR and CNR showed that the fat signal was significantly lower with 1:3:3:1 spectral spatial pulses than with 1:2:1 spectral spatial pulses ($P < .01$), whereas no difference in SNR was observed for the other tissues. This stronger fat suppression explains the better CNR with 1:3:3:1 spectral spatial pulses. As for the qualitative analysis, the homogeneity of fat suppression, conspicuousness of the lesion, and overall image quality were considered significantly better with the 1:3:3:1 pulse sequences ($P < .01$). On the contrary, artifacts, especially metallic ones, were significantly less intrusive with 1:2:1 pulses than with 1:3:3:1 pulses ($P < .05$) (Fig 5).

DISCUSSION

Fat signal suppression techniques are commonly used clinical applications in musculoskeletal MR imaging. Their addition to fast SE imaging sequences with long TRs results in greater conspicuousness of edema in regions with fat, such as bone marrow. They have also long been used in conjunction with both intravenous and intraarticular gadolinium-based enhancement. However, consistent and reliable fat signal suppression in a clinical environment can be challenging because of factors such as magnetic field inhomogeneity and tissue-induced susceptibility. Although these factors are, in part, intrinsic to the patient and the region studied, the means of applying fat saturation lend to an exaggeration of the artifacts produced. Conventional fat suppression techniques use a spectral but non–section-selective volumetric radio-frequency pulse (fat saturation pulse) to saturate the fat signal. On the contrary, spectral spatial pulses are simultaneously selective in space and resonant frequency (3). They can selectively excite water protons at any location, generating a fat-free image at that location. The spectral spatial pulse consists of a train of selective RF subpulses applied in conjunction with a section-selective gradient. Each subpulse in the train selects a section, while the phase accumulation from one subpulse to the other along the train is used to select the spectral frequency. This technique has been primarily used in conjunction with gradient-echo sequences (5,6,11,12), and, to a lesser extent, with

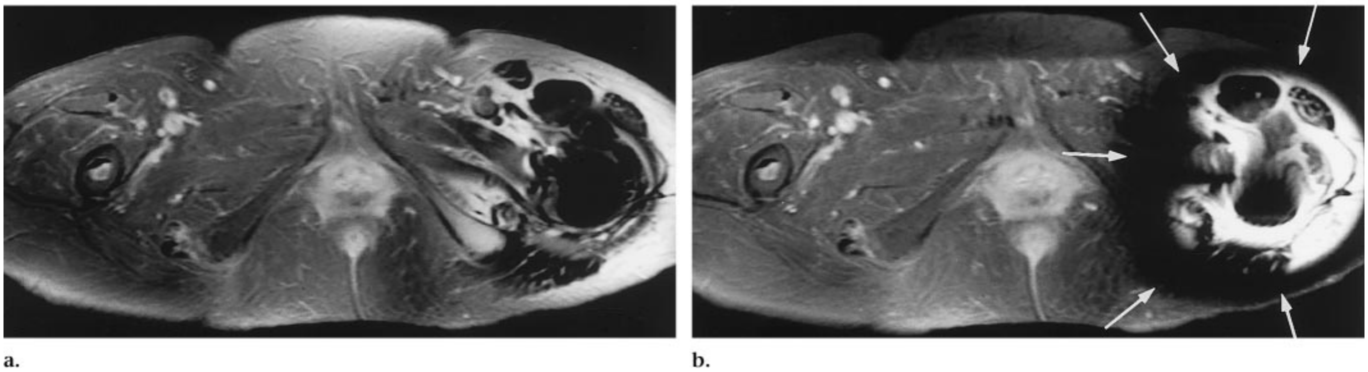


Figure 4. Transverse gadolinium-enhanced T1-weighted SE 500/17 MR images obtained in a 70-year-old man suspected of having sepsis after total hip replacement. Metallic artifacts (arrows) on images of the left hip are less marked with water excitation by means of **(a)** spectral spatial pulse than with **(b)** frequency-selective fat-saturation pulse.

spectroscopic sequences (18). Very few studies (8) have used this technique with SE and fast SE sequences, which are still the most widely used in current practice, particularly in musculoskeletal imaging.

The first finding of the present study is that water excitation is twice as fast as conventional fat saturation for sequences with short TRs (ie, T1-weighted SE sequences), because the conventional fat saturation technique requires an additional 25 msec per section and per TR, whereas water excitation adds only 3.45 msec per section and per TR. Therefore, with water excitation, a single package of 20 interleaved sections can be achieved within a TR of 500 msec. With fat saturation, for the same number of sections, an additional package (two TRs are needed to excite all the sections) is required, thereby doubling the acquisition time. Such a decrease in acquisition time is impossible in intermediate-weighted fast SE or T2-weighted fast SE sequences because the long TRs allow all the sections to be acquired within one package.

The 50% decrease in total acquisition time for water-excited T1-weighted sequences was achieved without deterioration of the quality of the image. Quantitative analysis showed a significant increase in SNR between the two types of images, whereas no change was observed in CNR. At qualitative analysis, visibility and margination of the lesion and overall image quality were considered better with the water excitation method by both raters. Potential applications in musculoskeletal imaging are numerous, since fat-suppressed T1-weighted sequences are commonly applied after either intravenous or intraarticular injection of gadolinium-based contrast material. For characterization of bone or soft-tissue tumors for which images can be acquired in multiple imaging planes after contrast material injection, the decrease in acquisition time could be substantial. Fat-suppressed T1-weighted images obtained after contrast material injection are the mainstay for the MR imaging evaluation of inflammatory or infectious processes. MR arthrography is also commonly used in sports medicine for many purposes (eg, diagnosis of joint instability, partial rotator cuff tears, and adhesive capsulitis). Moreover, a shorter imaging time may have a marked effect on image quality by reducing motion artifacts.

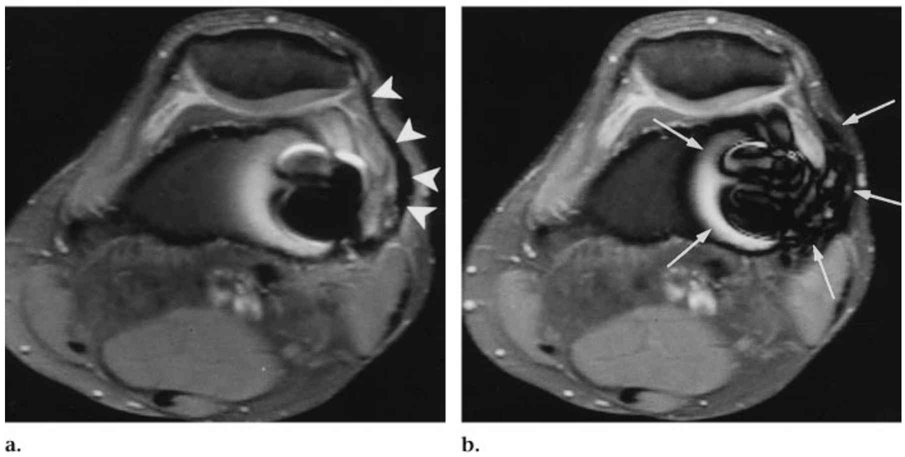


Figure 5. Transverse intermediate-weighted fast SE 2,200/17 MR images obtained with water excitation by means of spectral spatial pulse in a 33-year-old man with recurrent knee pain after anterior cruciate ligament repair. Metallic artifacts (arrows) are less marked with **(a)** 1:2:1 spectral spatial pulse than with **(b)** 1:3:3:1 spectral spatial pulse, thereby allowing better visualization, particularly of the lateral retinaculum (arrowheads).

Qualitative analysis revealed a better uniformity of fat suppression with spectral spatial pulses, a finding consistent with the data in the literature. By using a spectral spatial pulse for water excitation in fast SE sequences, Block et al (8) found that there was a clinically lower fat signal, with better uniformity than with spectrally selective presaturation techniques (fat saturation). In a recent study, Zur (14) confirmed that spectral spatial pulses suppress the fat signal better than conventional fat saturation does because of a lesser sensitivity to magnetic field variations. There are two main reasons for this. Spectral spatial excitation pulses excite each section only once per TR, whereas conventional fat saturation pulses excite each section every TR/N (N = number of sections). If the water resonance moves slightly toward the frequency of the saturation pulse because of a field variation, for example, a conventional fat saturation pulse will saturate it, whereas a spectral spatial pulse will only slightly affect it. Furthermore, as already emphasized, spectral spatial pulses selectively excite spins within a section, while fat saturation pulses are applied to the whole volume. This means that the quality of fat suppression depends on the frequency difference between water and fat within the whole volume for fat saturation and within the section for water excitation.

The increase in uniformity of fat suppression with water excitation is also related to a decrease in artifacts usually encountered with fat saturation. We noticed a marked decrease in foldover artifacts with water excitation. We also noticed a decrease in metallic artifacts due to a lesser susceptibility to magnetic field inhomogeneities, thereby allowing a better analysis of the structure next to metallic implants. This can be partially explained by the fact that the spectral spatial pulses use greater bandwidth and larger section-selective gradients than those of conventional excitation. This could be of particular interest in MR imaging of patients with total joint replacement.

Increases in SNR and CNR, better uniformity of fat suppression, and reduction of artifacts explain why images obtained with water excitation by means of spectral spatial pulses were considered of better overall quality and were diagnostically more useful than fat-saturated images for all sequences. The total number of detected lesions was the same with both methods of fat suppression. Both margination and visibility of lesions, however, especially on T1-weighted SE and T2-weighted fast SE images, were better with water excitation than with fat saturation.

The advantages of using water excitation, particularly the decrease in acquisition time in T1-weighted sequences, are slightly offset by certain aspects. The present study required the application of strictly identical parameters in both fat suppression techniques to enable valid comparison. In current practice, it would be possible to reduce the acquisition time of fat saturation by modifying parameters to prevent doubling the acquisition time. One possibility would be to decrease the number of sections obtained and to increase section thickness to offset the decreased coverage, if needed. Another possibility would be to increase the TR, which would, at the cost of a substantial increase in acquisition time, allow the possibility of achieving more sections in a single package. However, both possibilities have a marked effect on the conspicuousness of lesions (partial volume effects if thicker sections are obtained and decreased tissue and/or lesion contrast if longer TR is used).

The water excitation method has disadvantages. Slight inhomogeneities in fat suppression could be observed in the subcutaneous soft tissues (Fig 3). These seemed more frequent and pronounced in tissues in contact with a surface coil. They did not interfere with interpretation, however, since they were localized in the subcutaneous tissues away from the ROI.

Another shortcoming of the water excitation method is section thickness. In our study, thickness was limited to 5.7 mm because of software limitations. With improved versions, it is now possible to decrease the thickness in SE sequences to 4.5 mm without modifying the section profile. At present, thinner sections in SE sequences cannot be achieved without degrading the section profile and, thus, the quality of the images. However, it is possible to obtain 1-mm sections by using three-dimensional gradient-echo sequences that have been used in most previous experimental studies (6,12).

Comparison between 1:2:1 and 1:3:3:1 spectral spatial pulses showed stronger fat suppression and, therefore, a better CNR between tissues containing fat (eg, fat and bone marrow) and the other tissues with 1:3:3:1 spectral spatial pulses. Because of a higher selectivity in water resonant frequency and therefore a lesser probability of exciting tissues other than water, fat suppression with 1:3:3:1 pulses was qualitatively considered of better uniformity by both raters. When present, a significant reduction in inhomogeneities of subcutaneous soft tissues was also observed. On the contrary, there was a significant reduction in metallic artifacts with 1:2:1 spectral spatial pulses, probably because metallic implants induce marked dephasing of the neighboring spins. The longer the excitation pulse, the greater the dephasing. Therefore, a three-element (1:2:1) composite pulse induces less dephasing than a four-element (1:3:3:1) composite pulse. In current practice, it seems more appropriate to use 1:3:3:1 pulses with the water excitation technique, except in the case of metallic implants, for which 1:2:1 pulses are more appropriate.

In conclusion, the results of this preliminary study show that water excitation by means of spectral spatial pulses has many advantages when compared with the conventional fat saturation technique: a significant decrease in acquisition time (by up to 50%) in T1-weighted SE sequences, a greater SNR and CNR (for CNR, only in intermediate-weighted sequences), and a better uniformity of fat suppression with a reduction of foldover and metallic artifacts, giving the lesions more conspicuousness and the images a better overall quality. The disadvantages of using spectral spatial pulses at present are the current limitation of a 4.5-mm section thickness on two-dimensional SE images and the possible occurrence of inhomogeneities in the subcutaneous soft tissues generally in contact with the coil.

References

1. Delfaut EM, Beltran J, Johnson G, Rousseau J, Marchandise X, Cotten A. Fat suppression in MR imaging: techniques and pitfalls. RadioGraphics 1999; 19:373–382.
2. Krinsky G, Rofsky NM, Weinreb JC. Nonspecificity of short inversion time inversion recovery (STIR) as a technique of fat suppression: pitfalls in image interpretation. AJR Am J Roentgenol 1996; 166:523–526.
3. Meyer CH, Pauly JM, Macovski A, Nishimura DG. Simultaneous spatial and spectral selective excitation. Magn Reson Med 1990; 15: 287–304.
4. Mao J, Yan H, Bidgood WD Jr. Fat suppression with an improved selective presaturation pulse. Magn Reson Imaging 1992; 10:49–53.
5. Meyer CH, Hu BS, Nishimura DG, Macovski A. Fast spiral coronary artery imaging. Magn Reson Med 1992; 28:202–213.
6. Thomasson D, Purdy D, Finn JP. Phase-modulated binomial RF pulses for fast spectrally-selective musculoskeletal imaging. Magn Reson Med 1996; 35:563–568.
7. Schick F, Forster J, Machann J, Huppert P, Claussen CD. Highly selective water and fat imaging applying multislice sequences without sensitivity to B1 field inhomogeneities. Magn Reson Med 1997; 38:269–274.
8. Block W, Pauly J, Kerr A, Nishimura D. Consistent fat suppression with compensated spectral-spatial pulses. Magn Reson Med 1997; 38:198–206.
9. Morrell G, Macovski A. Three-dimensional spectral-spatial excitation. Magn Reson Med 1997; 37:378–386.
10. Schick F, Forster J, Machann J, Kuntz R, Claussen CD. Improved clinical echo-planar MRI using spatial-spectral excitation. J Magn Reson Imaging 1998; 8:960–967.
11. Forster J, Schick F, Breuer J, Sieverding L, Lutz O. Slice-selective fat saturation in MR angiography using spatial-spectral selective prepulses. J Magn Reson Imaging 1998; 8:583–589.
12. Hardy PA, Recht MP, Piraino DW. Fat suppressed MRI of articular cartilage with a spatial-spectral excitation pulse. J Magn Reson Imaging 1998; 8:1279–1287.
13. Schick F. Simultaneous highly selective MR water and fat imaging using a simple new type of spectral-spatial excitation. Magn Reson Med 1998; 40:194–202.
14. Zur Y. Design of improved spectral-spatial pulses for routine clinical use. Magn Reson Med 2000; 43:410–420.
15. Kaufman L, Kramer DM, Crooks LE, Ortendahl DA. Measuring signal-to-noise ratios in MR imaging. Radiology 1989; 173:265–267.
16. Gudbjartsson H, Patz S. The Rician distribution of noisy MRI data. Magn Reson Med 1995; 34:910–914.
17. Altman DG. Comparing groups: continuous data. In: Practical statistics for medical research. London, England: Chapman & Hall, 1991; 407–409.
18. Adalsteinsson E, Spielman DM, Wright GA, Pauly JM, Meyer CH, Macovski A. Incorporating lactate/lipid discrimination into a spectroscopic imaging sequence. Magn Reson Med 1993; 30:124–130.