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MR Imaging of Joints: Analytic Optimization of GRE Techniques at 1.5 T

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To clarify the choice of imaging parameters for optimal gradient-recalled echo MR scanning of joints, we analyzed the behavior of contrast-to-noise and signal-to-noise ratios for spoiled (i.e., fast low-angle shot [FLASH] or spoiled GRASS) and steady-state (i.e., gradient-recalled acquisition in the steady state [GRASS] or fast imaging with steady precession) techniques at 1.5 T. The analysis is based on tissue characteristics derived from spin-echo measurements of hyaline cartilage and synovial fluid signal in the patellofemoral joints of 11 volunteers. Separate analysis of contrast-to-noise and signal-to-noise ratios for multiplanar (long TR) acquisitions shows that these parameters are each improved compared with single-slice methods. At TRs greater than 250 msec, there is no significant difference in the contrast behavior of FLASH and GRASS.

For optimal contrast-to-noise ratio (synovial fluid–cartilage), the best multiplanar sequence (for TE <23 msec) is with a short TE and a large flip angle (e.g., 400/9/73° [TR/TE/flip angle]). If a single-scan or three-dimensional technique is desired, then a GRASS sequence at minimal TR and TE and intermediate flip angle (18/9/32°) is best. For optimal signal-to-noise ratio (for both synovial fluid and hyaline cartilage), the best multilplanar sequence uses a short TE and an intermediate flip angle (e.g., 400/9/30°). If a short TR, high signal-to-noise technique is desired, then GRASS (18/9/13°) is superior to FLASH.


Gradient-recalled echo (GRE) techniques have gained wide popularity in musculoskeletal MR imaging; they have been specifically helpful for the evaluation of joints. These techniques provide high contrast between articular cartilage, synovial fluid, and fibrocartilaginous structures, frequently at a significant time savings as compared with spin-echo imaging.

Recommendations for GRE scanning parameters are largely empirical. For evaluation of degenerative changes in hyaline cartilage, short TR (33 msec) fast imaging with steady precession (FISP) with a flip angle of 70° has been advocated [1]. For imaging of the glenoid labrum, long TR (300 msec) gradient-recalled acquisition in the steady state (GRASS) sequences with flip angles of 90° have been proposed [2]. Short TR (30 msec) fast low-angle shot (FLASH) sequences with a flip angle of 12° have been suggested for the general evaluation of articular cartilage [3].

This study analyzes the contrast and signal behavior of synovial fluid and hyaline cartilage in an effort to provide objective data on which the choice of parameters for articular imaging can be based. Two major GRE scan techniques will be examined: (1) spoiled fast techniques, or those with incoherent dephasing after the echo (FLASH, spoiled GRASS [SPGR]), and (2) steady-state fast techniques with coherent dephasing after the echo (GRASS, FISP, fast steady state [FAST], resonant offset average steady state [ROAST]). For purposes of clarity, the first type of scan will subsequently be referred to as FLASH and the second as GRASS.
Signal and Contrast Formulas

Analytic signal expressions for field-echo sequences have been summarized by van der Meulen et al. [4]. Defining $E_1 = \exp(-TR/T1)$, $E_2 = \exp(-TR/T2)$, $a = [1 - E_1 \times E_2^2 + \cos(\alpha) \times (E_2^2 - E_1)](1 - E_1)$, $b = [1 + \cos(\alpha)] \times E_2$, $c = [(1 + \cos(\alpha)) - a]/(a^2 - b^2)] + 1$, and rho = proton density, the signal intensity (S) for a FLASH sequence can be expressed as:

$$S = \rho \times \sin(\alpha) \times (1 - E_1) \times \exp(-TE/T2)/(1 - E_1 \times \cos(\alpha)). \quad (1)$$

The signal intensity (S) for a GRASS sequence may be expressed as:

$$S = \rho \times \sin(\alpha) \times c \times \exp(-TE/T2)/(1 + \cos(\alpha)). \quad (2)$$

These expressions are based on the following assumptions: slice profiles are rectangular, T2 equals T2*, and RF excitations are not phase alternated. In the case of GRASS, it is further assumed that the phase distribution of transverse magnetization is uniformly distributed from 0 to $2\pi$ within voxels. Deviations from the ideal slice profile probably account for the major inaccuracies in analytic signal estimations. Analytic corrections for variations in slice profile are difficult to implement because deviations in slice profile are not systematic [5]. On current state-of-the-art systems, the second assumption is reasonable [6] if susceptibility and chemical-shift effects can be ignored (significant signal-determining factors in the marrow space and in fat, respectively).

In analyzing tissue signal-to-noise (S/N) and contrast-to-noise (C/N) ratios, a normalization for scan time is necessary such that comparisons are practically meaningful. Assuming the number of phase-encoding steps remains constant from scan to scan, the number of possible signal averages will be inversely proportional to the TR. Because noise is inversely proportional to the square root of the number of signal averages, the following expressions can be used in the case of single-slice acquisitions:

$$S/N = |S|/(TR)^{n/2} \quad (3)$$

and

$$C/N = |S_i - S_j|/(TR)^{n/2}. \quad (4)$$

where S represents the signal value for the tissue of interest. $S_i$ and $S_j$ are the signal intensities of hyaline cartilage or synovial fluid. Noise and receiver bandwidth are assumed to be constant for each imaging experiment.

In the case of an interleaved multislice acquisition, the total imaging time per slice is proportional to TR divided by $n$, where $n$ represents the number of slices obtained per multislice acquisition. Thus, the appropriate time-adjusted expressions for the multislice acquisition become:

$$S/N = |S|/(TR/n)^{n/2} \quad (5)$$

and

$$C/N = |S_i - S_j|/(TR/n)^{n/2}. \quad (6)$$

It is possible to estimate $n$ with reference to a machine-dependent time value we will refer to as $t$:

$$n = TR/(TE + t). \quad (7)$$

Values for $t$ are limited by the same constraints as are the boundary values for minimum TR. The minimum TR for a given TE is determined by the time required for sampling of the echo and rephasing spatial-encoding gradients. This time will be greater with scanning options such as presaturation and may vary with slice thickness. If no scanning options are used, the minimum TR is taken to equal TE plus 9 msec ($t = 9$ msec). If presaturation is used, $t$ becomes 26 msec for GRASS and 19 msec for FLASH. These values are based on figures applicable to the General Electric Signa (4.1) unit.

With constant measuring time (bandwidth) and full echo sampling, 9 msec is taken to be the minimum TE. This minimum value dictates a minimum field of view. For the sake of simplicity, multiplanar S/N or C/N estimations will pertain to the optimal case.

The S/N and C/N expressions for three-dimensional (3-D) acquisitions would be the same as in equations 5 and 6, but $n$ would be independent of TR. Thus, the optimal 3-D sequences should be the same as those recommended by the single-slice optimization (equations 3 and 4), although the actual S/N and C/N would be increased by a factor of $n^2$. However, fixed parameters such as the minimum achievable TR and field of view may be different. As dictated by fast Fourier reconstruction techniques, the number of slices in 3-D imaging is restricted to powers of two (typically 32 or greater).

Subjects and Methods

Imaging of the patellofemoral joint was performed in asymptomatic volunteers on a 1.5-T system (Signa 4.1, General Electric, Milwaukee, WI) with a 17-cm transmit-receive birdcage extremity coil. Spin-echo images were acquired by using a 10-cm field of view, 4-mm axial slices with a 4-mm interslice gap, 256 × 256 matrix, and one or two excitations. Regions of interest were measured with manufacturer-provided software.

Seven subjects were imaged by using the following sequences (protocol 1): (1) 250–300/25 (TR/TE), (2) 850/25, (3) 1400/25, and (4) 2000–2300/25,50,75,100. Six subjects were imaged by using the following sequences (protocol 2): (1) 6000/25 and (2) 2300–3000/25,50,75,100. Eleven subjects were imaged, two subjects were imaged in both protocols. Signal values were measured in both the basal and superficial aspects of the patellar cartilage in the region of the patellar apex, and from synovial fluid in the peripatellar synovial recesses, or deep to the retinaculum over the femoral condyles. Regions of interest ranged in size from 4 to 29 mm² for cartilage and from 3 to 33 mm² for synovial fluid.

T1 and rho values for cartilage were derived from data in protocol 1. T1 and rho values for synovial fluid were derived from data in protocol 2. Data from the multiecho acquisitions in both protocols were used to compute T2 values for both cartilage and synovial fluid.
T1 and T2 values were derived from the following signal expression for a spin-echo sequence:

\[ S = \rho \mathrm{h}[1 - \exp(-TW/T1)]\exp(-TE/T2). \]  

(8)

where TW = TR - TE. An accurate signal expression can be obtained in the multiecho case by using TW = TR - N \times TE, where N = number of echoes obtained for the multiecho acquisition [7].

Assuming monoexponential decay, T1 and T2 values were computed by using a two-parameter, chi-square minimization curve fit. Signal values less than twice the magnitude of background signal were disregarded. Rho values were obtained via substitution of calculated T1 and T2 values into equation 8 by using the data from the longest TR, short TE sequence for each subject. Differences in tissue characteristics for superficial and basal laminae of patellar cartilage were compared by using a paired t test.

Contrast was optimized by using the characteristics of the superficial lamina of patellar cartilage. Contrast is discussed with respect to being either positive (synovial fluid signal > hyaline cartilage signal) or negative (synovial fluid signal < hyaline cartilage signal). Two numerical optimization procedures were performed: (1) maximizing the lesser of either the S/N (equation 5) for synovial fluid or hyaline cartilage (or) maximizing the C/N (equation 6) between synovial fluid and the hyaline cartilage.

**Results**

On the spin-echo images of the patellar cartilage, a gradation in signal could generally be discerned on the long TR/short TE images, with increasing signal noted in the more superficial aspects of the patellar cartilage. This gradation was inapparent on the short TR (300 msec) images. In two patients, this gradation in signal was generally much less prominent. In no case was the demarcation between superficial and basal zones well defined. T1, T2, and rho values were not significantly (\( p < .05 \)) different in superficial and basal aspects of patellar cartilage. The tissue characteristics obtained are presented in Table 1.

Signal and contrast for both GRASS and FLASH increase asymptotically with increasing TR values for appropriate alpha values regardless of the TE. Hence, discussion of optimal S/N or C/N will pertain to time-adjusted contrast (according to equations 3–6). For illustrative purposes, a TR of 400 msec will be chosen in discussing long TR (multiplanar) acquisitions, since this value would be fairly typical of many clinical applications (providing approximately 10–20 slices, depending on scan options).

**TABLE 1: Measured Tissue Characteristics (1.5 T)**

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Measured Value ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1 (msec)</td>
</tr>
<tr>
<td>Cartilage (superficial)</td>
<td>1089 ± 97</td>
</tr>
<tr>
<td>Cartilage (basal)</td>
<td>911 ± 240</td>
</tr>
<tr>
<td>Synovial fluid</td>
<td>3176 ± 461</td>
</tr>
</tbody>
</table>

Note.—Units for rho (proton density) are arbitrary.

**GRASS S/N (Optimization 1)**

TR-adjusted signal for field echoes generally increases for shorter TE and TR values. Maximal S/N for GRASS occurs at the minimal TE and TR values: 18/8/14° (TR/TE/flip angle); S/N = 14.73 for hyaline cartilage and 18.48 for synovial fluid (signal values are in arbitrary units). If the minimal attainable TR is 35 msec (e.g., with presaturation), the maximum occurs at 35/9/15°, with S/N = 14.40 for hyaline cartilage and 15.25 for synovial fluid. The flip-angle dependence at these small TR values is shown in Figure 1 for the nonpresaturation sequence.

For long TR values (>200 msec), relative maxima also occur at minimum TE values (9 msec) and an appropriately larger alpha. For TR = 300, 400, and 500 msec, alpha = 26°, 30°, and 33°, respectively, with S/N of 12.80–12.88 for hyaline cartilage and 12.74–12.76 for synovial fluid. In the range of appropriate alpha values, the losses in S/N for these sequences are relatively minor with changes in TR, particularly for the longer TR sequences (Fig. 2A). Very little contrast between synovial fluid and hyaline cartilage can be expected in this range. The flip-angle dependence at these longer TR values is shown in Figure 2B.

Considering a multiplanar acquisition, the S/N would be 42.75 for hyaline cartilage and 42.25 for synovial fluid for the TR = 400 msec sequence with t = 26 msec. 2.93 times that of the optimal single-slice case (35/9/15°) with the same t value.

A 400/9/30° GRASS image is illustrated in Figure 3. The measured S/Ns of hyaline cartilage and synovial fluid (relative to those for a 400/23/18° sequence) are 2.1% less and 11.3% more than predicted, respectively.

**FLASH S/N (Optimization 1)**

Signal is diminished for FLASH as compared with GRASS at short TR values for all but the smallest flip angles (<10°),
particularly for synovial fluid (Fig. 4, compare with Fig. 1). On FLASH sequences at low flip angles, hyaline cartilage exhibits greater signal than synovial fluid, but synovial fluid exhibits a more gradual and sustained increase in signal with increasing TR.

The optimal FLASH sequence is 22/9/7° with S/N = 12.76 for synovial fluid and 12.77 for hyaline cartilage. With these parameters, almost no contrast between synovial fluid and hyaline cartilage can be expected. For TE = 9 msec, and a minimum TR of 28 msec, the optimal alpha is 8°, with S/N = 12.75 for synovial fluid and 12.85 for hyaline cartilage.

For longer TR values (>250 msec, the multislice case), signal behavior is essentially identical to that for GRASS, as discussed above.

**GRASS C/N (Optimization 2)**

The optimal contrast for GRASS occurs at a positive-contrast maximum: 18/9/32°, C/N = 6.52 (contrast values are in arbitrary units). This short TR maximum reflects the generally higher signal values of synovial fluid with GRASS.
as compared with FLASH at short TR values (less than approximately 150 msec), particularly at intermediate and large flip angles (30°-90°). This short TR minimum is quite sensitive to T1 (Fig. 5). For a minimum TR of 35 msec (e.g., using presaturation), the global maximum diverges to long TR values. For 359/35° images, C/N is only 2.65.

In the range of short TR values, there is a mild contrast loss for changes in flip angle, but positive contrast for GRASS (Fig. 6) is slightly less sensitive to changes in flip angle than is short TR, negative contrast for FLASH.

A negative-contrast long TR maximum occurs for GRASS if we limit TE < 23 and TR < 600 msec: 433/9/75°, C/N = −4.54. Changes in TR effect little C/N loss in this range (Fig. 7A). For the long TR acquisition, the negative-contrast maximum (short TE scan, Fig. 7B) is less sensitive to changes in flip angle than is the positive-contrast maximum (longer TE scan, Fig. 7B).

In the multiplanar case, the C/N of the 433/9/75° sequence is −15.74 with a t = 26 msec, 2.41 times that of the short TR (18 msec), positive-contrast maximum with a t = 9 msec.

Positive C/N can be achieved at long TR by using longer TEs. For 400/23/18°, the C/N is equivalent to that with the TE = 9 msec, negative-contrast sequence. An image with TE = 23 msec is shown in Figure 8. The measured contrast, normalized to synovial fluid signal, is 11.5% greater than the predicted contrast.

**FLASH C/N (Optimization 2)**

If TE is limited to less than 25 msec and TR to less than 600 msec, a short TE, negative-contrast maximum occurs for FLASH: 23/9/20°, and C/N = −4.70 (Figs. 5 and 6). If the minimum TR is 28 msec (e.g., with presaturation), the optimal TE is 9 msec and flip angle is 22°, with almost identical C/N = −4.70. Thus, negative-contrast short TR FLASH is less sensitive to changes in TR than is positive-contrast short TR GRASS. In this sense, short TR FLASH may be more versatile in providing high C/N for single-slice and 3-D acquisitions, certainly if presaturation is used. In the range of short TRs, minor changes in flip angle cause significant contrast losses (Fig. 6).

Long TR (>250 msec) contrast behavior is almost identical to GRASS (as discussed above).

**3-D Imaging**

The optimal scan parameters for 3-D imaging are the same as for single-slice imaging. For a 32-slice acquisition with presaturation, our analysis would predict 14% greater S/N for 3-D GRASS (35/9/15°), as compared with two-dimensional (2-D)/multiplanar FLASH (896/9/44°). Because C/N in short TR GRASS is very sensitive to the minimum achievable TR, FLASH (28/9/22°) is more versatile for optimal C/N in 3-D acquisitions (e.g., if presaturation is used). Again, for a 32-slice acquisition with presaturation, our analysis would predict 11% greater C/N for the 3-D FLASH (28/9/22°) acquisition, as compared with multiplanar FLASH (869/9/95°).

**Error Estimates**

The theoretical results are fairly sensitive to variations in the measured tissue characteristics. To illustrate the influence of these variations, we can adjust all the tissue parameters for hyaline cartilage and synovial fluid by one standard deviation to effect signal changes for these tissues in opposite directions: decreasing T1 and increasing T2 and rho for hyaline cartilage, increasing T1 and decreasing T2 and rho for synovial fluid. The optimal S/N for a FLASH sequence is then obtained with 45/9/9°; the S/N would be 49% greater than for a (previously optimal) 22/9/7° sequence. The optimal S/N for a GRASS sequence is then obtained with 9/18/16°; the S/N would be 37% greater than for a (previously optimal)
Discussion

The patellofemoral joint was selected for study because of its accessibility to imaging and the large size of the patellar cartilage. Attention has been given to the bilaminar appearance of the patellar cartilage as depicted on T1- or proton-density-weighted images [8, 9], with hypointensity noted in the basal zone. These zones were not uniformly or discretely defined in our subjects.

Limitations to an analytic optimization result largely from inaccuracies in T1, T2, and rho determinations. In the study of cartilage and synovial fluid, the small volume of these tissues poses problems of sampling error due to volume averaging. While our region-of-interest measurements were sufficiently small to isolate tissues of interest within each image, volume averaging in the slice-thickness (4-mm) dimension probably accounts for some measurement variability. Perhaps more important, problems optimizing MR scan techniques may also result from physiologic and intersubject variations in tissue characteristics. Despite these limitations, some generalizations about tissue characteristics are necessary to clarify the choice of imaging parameters and to facilitate a greater understanding of particular imaging strategies.

An analysis of the optimization results is directed by two major considerations. First, clinical imaging at long TE values is limited by dephasing due to susceptibility effects and field inhomogeneities, although C/N may be enhanced for specific tissues. Second, clinical imaging is regularly performed with multplanar acquisitions. On this basis, long TR scans afford sizeable advantages in overall S/N and C/N as compared with single-slice techniques, but greater susceptibility to motion artifact can compromise this theoretical advantage to some
degree. At longer TRs (>250 msec), FLASH and GRASS are essentially equivalent.

The indications for 3-D imaging are generally distinct from those for conventional techniques; that is, applications requiring thin contiguous slices and large numbers of slices (generally, 32 or more). Thus, our comparison of 2-D and 3-D imaging results is somewhat artificial. Volume imaging benefits from greater signal averaging due to phase encoding in a second (slice-selection) dimension, giving it an intrinsic advantage in S/N. This advantage becomes more pronounced with larger numbers of slices, although in reality, this advantage is generally offset by thinner slice thicknesses. The optimal scan parameters for 3-D imaging would be the same as for single-slice imaging.

In the short TR case, GRASS offers 15% greater S/N than does FLASH. If the minimal TR is 35 msec (as with presaturation), then the S/N for GRASS is 13% greater than that for the FLASH sequence. S/N for a multislice acquisition with a TR of 400 msec will be 2.9 times that of the single-slice acquisition with a TR of 18 msec.

Optimal negative contrast occurs for FLASH at minimal TE and short TR values (23/9/20°) if only TE values less than 24 msec are considered. Optimal contrast for GRASS occurs at the minimum TE and TR (18/9/32°). This short TR maximum is a positive-contrast maximum, but at a short TE. This maximum for GRASS no longer exists if options are used that lengthen the minimal TR (e.g., to 35 msec with presaturation). C/N for a 35/9/35° GRASS sequence is only 41% of that for a sequence with a TR of 18 msec. Hence, for optimal C/N, FLASH is preferred for 3-D or single-slice imaging if presaturation is used.

If the minimum achievable TR becomes longer (i.e., 35 msec), a long TR/short TE sequence (433/9/75°) becomes the globally optimal technique (negative contrast). If the multiplanar acquisition is considered, then the overall C/N for this scan is 2.4 times that of the 18/9/32° sequence. If positive contrast is desired in the multiplanar case, longer TEs can be used, although slice coverage and S/N will be less than for the negative-contrast multiplanar technique.

In summary, optimal S/N from both cartilage and synovial fluid may be desirable for assessment of low-signal intraarticular structures such as fibrocartilaginous labra and menisci. For this purpose, the optimal multiplanar GRE acquisition would have a minimal TE and intermediate flip angle (e.g., 400/9/30°). For a single-slice or 3-D acquisition, GRASS (18–35/9/14–15°) would be superior to FLASH. Evaluation of intrinsic cartilage lesions may be facilitated by optimizing C/N between synovial fluid and hyaline cartilage. The optimal multiplanar acquisition for this purpose would have a minimal TE and a large flip angle (e.g., 400/9/73°). This sequence would have a T1-weighted appearance with synovial fluid hypointense relative to hyaline cartilage. If an arthrographic effect is desired (i.e., with synovial fluid hyperintense relative to hyaline cartilage), a longer-TE multislice GRE sequence may be used (e.g., 400/17/23/16–18°). Alternatively, if a single-slice or 3-D positive-contrast technique is desired, a minimal-TR, minimal-TE, intermediate-flip-angle GRASS sequence is best (e.g., 18/9/32°). However, the short TR required in this case precludes the use of scanning options such as presaturation.

The ultimate utility of specific GRE sequences will depend on more than singular contrast considerations. We hope, however, that a greater knowledge of GRE contrast behavior with respect to articular tissues will objectify the application of various imaging schemes.

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