

# Magnetic Resonance Imaging of Superficial Cartilage Lesions: Role of Contrast in Lesion Detection

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**Excised patellar cartilage phantoms with artificial surface lesions were imaged in a 2 g/dl albumin solution to determine the effect of cartilage/fluid contrast on detection of early degenerative change. Surface lesions consisted of full-thickness holes, superficial grooves, and coarse abrasion. Phantoms were imaged with a T1-weighted fast low-angle shot (FLASH) and T2\*-weighted dual-echo in the steady state (DESS) sequence. Although both sequences were able to identify full-thickness holes, they underestimated the presence of superficial grooves and extent of fibrillation. Despite greater bulk tissue contrast between cartilage and fluid for the FLASH sequence, detection of fibrillation was poorer compared with the DESS images. The results of this study suggest that surface properties of fibrillated cartilage contribute significantly to the insensitivity of magnetic resonance imaging in detecting superficial lesions. In contrast to previous papers suggesting that T1-weighted spoiled gradient-echo imaging provides the greatest accuracy for lesion detection, our results indicate that, in the presence of joint fluid, T2\*-weighted imaging increases detection of superficial lesions. J. Magn. Reson. Imaging 1999;10:178-182. © 1999 Wiley-Liss, Inc.**

**Index terms:** magnetic resonance imaging (MRI); cartilage, osteoarthritis, fibrillation, joints

OSTEOARTHRITIS arthritis (OA) is a multi-factorial disease characterized by degeneration and ultimate loss of articular cartilage. Studies in animal models of OA indicate that early cartilage degeneration begins in the superficial layer (1). One of the earliest structural changes is fine fibrillation, which leads to ulceration and fissuring (2). Several clinical studies have shown that MRI is insensitive to these early findings (3-5). Relatively few studies have attempted to identify factors responsible for the insensitivity of MRI in detection of early superficial damage. Using an excised patellar model, Rubenstein and colleagues concluded that cur-

rent clinical protocols have insufficient resolution and signal-to-noise ratio to detect cartilage fibrillation (6). The role of tissue contrast in detection of surface lesions remains unclear. Our initial clinical experience led us to hypothesize that T2-weighting was necessary to detect superficial fibrillation and suggested that contrast between synovial fluid and cartilage was an important factor in lesion identification. The purpose of this study was to evaluate the role of contrast between cartilage and joint fluid in the detection of superficial cartilage lesions using a controlled phantom study.

## MATERIALS AND METHODS

### Sample Preparation

Nine phantoms with lesions of the articular surface were constructed from freshly excised porcine patellae. Cartilage lesions consisted of three full-thickness holes measuring 1, 1.5, and 1.75 mm in diameter; 3 superficial fissures measuring 1 mm deep by 1.5 mm wide by 6 mm long aligned 0°, 45°, and 90° to the acquisition plane, and coarse abrasion of the outer 25% of cartilage involving 20-50% of the articular surface. The phantoms were submerged in 2 g/dl albumin in saline (Sigma, St. Louis, MO) and imaged immediately following preparation.

### MR Imaging

Sagittal images were obtained on a Siemens 1.0 T Magnetom Impact Expert Clinical scanner (Siemens Medical Systems, Erlangen, Germany) using a 20 cm circularly polarized extremity coil. All phantoms were imaged with the articular surface perpendicular to the B0 field. The image protocol consisted of 1) a three-dimensional (3D) dual-echo in the steady state (DESS) sequence (TR/TE 36/9 msec, flip angle 35°); and 2) a 3D fat-suppressed fast low-angle shot (FLASH; TR/TE 48/11 msec, flip angle 30°) sequence. For both sequences, a rectangular field of view of 9 × 18 cm was used with a 128 × 256 matrix. Images were acquired with both a 1 and 2 mm section thickness, using a single acquisition (NA = 1). For the 3D FLASH protocol, additional acquisitions were obtained of six phantoms with a 256 × 512 matrix, and three signal averages.

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To determine whether contrast between the albumin solution and articular cartilage was an accurate model of physiologic contrast, the signal difference to noise ratio (SDNR) of the albumin solution/cartilage in the nine phantoms was compared with the SDNR of synovial fluid/cartilage in 17 patients imaged with identical scan parameters; and a section thickness of 2 mm.

**Data Analysis**

After imaging, the cartilage surface was stained with methylene blue and photographed with a Kodak D-40 digital camera (Eastman Kodak, Rochester, NY). The digital images were manually segmented using Adobe Photoshop software (Adobe Systems, Mountain View, CA) at a resolution of 0.35 mm/pixel, and the extent of fibrillation was determined as a percent surface area of the articular surface. This was used as the reference standard. A single observer without knowledge of the photographic results performed analysis of the MR image. For each MR image, the length of the abraded surface and the total articular surface were measured, multiplied by section thickness, and integrated to calculate the percent surface area of abrasion. This was compared with the photographic standard to determine bias. Comparison of bias between the DESS and FLASH images obtained using equivalent section thickness was made using a two-tailed paired Student's *t*-test ( $P < 0.05$ ) and assumed unequal variance. Both holes and grooves were reported as either observed or not observed to determine the rate of detection.

**RESULTS**

Results for the SDNR measurements are presented in Table 1. For DESS images, synovial fluid is hyperintense to cartilage, resulting in a negative value for the SDNR. At comparable voxel size the 3D FLASH sequence produced greater absolute SDNR. For the highest resolution FLASH images (256 × 512 matrix) obtained with three signal averages, the absolute SDNR is not statistically different from the lower resolution DESS images obtained with equivalent section thickness ( $P =$

Table 1  
Comparison of Signal Difference to Noise Ratio (SDNR) Between Articular Cartilage and Fluid for Phantom and Patient Images

Pulse sequence	SDNR ± σ
DESS 1 mm	-4.6 ± 1.1
DESS 2 mm	-5.9 ± 1.3
FLASH 1 mm	5.3 ± 1.4
FLASH 2 mm	7.4 ± 2.0
FLASH 1 mm (512 NA = 3)	3.8 ± 0.7
FLASH 2 mm (512 NA = 3)	5.2 ± 1.0
Patients (2 mm DESS)	-5.7 ± 1.2
Patients (2 mm FLASH)	7.3 ± 1.8

The term (512 NA = 3) indicates acquisition with a 512<sup>2</sup> matrix, and three signal averages. Note that the SDNR for the DESS images is negative, indicating that cartilage is less intense than fluid. At equivalent voxel size, the absolute SDNR is greater for the FLASH images compared with the DESS images. There is no statistically significant difference between the SDNR of the patient and phantom images ( $P > 0.10$ ).

Table 2  
Detection Rate for Cartilage Holes and Grooves

Pulse sequence	Holes (%)	Grooves (%)
DESS 1 mm	71.8	55.3
DESS 2 mm	66.2	49.8
FLASH 1 mm	77.3	66.7
FLASH 2 mm	66.0	55.3
FLASH 1 mm (512 NA = 3)	88.7	55.0
FLASH 2 mm (512 NA = 3)	88.7	55.0

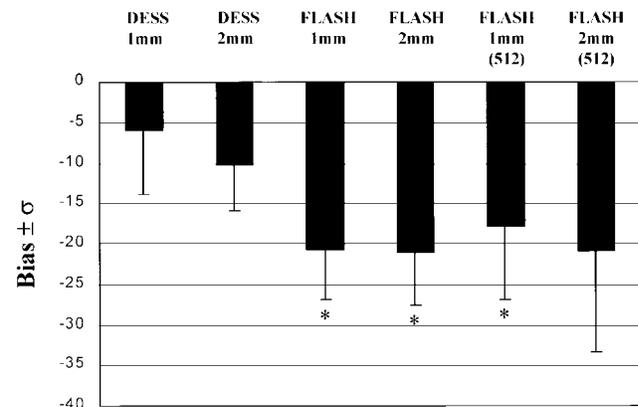
0.12 for 1 mm and  $P = 0.28$  for 2 mm). There was no statistically significant difference between the SDNR of images obtained with phantoms or human patients (DESS:  $P = 0.81$ , FLASH:  $P = 0.97$ ).

The overall detection rate for full-thickness cartilage holes and superficial cartilage grooves is presented in Table 2. The detection of holes was similar for the DESS and FLASH sequences. With the exception of the 256 × 512 matrix FLASH images, in which detection was equivalent, higher detection rates were obtained using 1 mm sections and a higher image matrix. All sequences performed poorly in detection of superficial grooves. For the FLASH images, detection was not significantly improved with higher resolution images.

The error in determination of percent-fibrillated surface area is presented in Fig. 1. As indicated by the negative bias, all images underestimated the extent of surface fibrillation. The difference in bias was consistently larger for the FLASH images. In comparison with DESS images obtained with equivalent section thickness, the difference in bias was statistically significant for the low-resolution FLASH images, as well as higher resolution FLASH images obtained with 1 mm section thickness.

**DISCUSSION**

The development of therapeutic agents for management of patients with OA requires non-invasive biomarkers to



**Figure 1.** Error in determination of percent fibrillated surface area. The term (512) refers to FLASH acquisitions obtained with a 512<sup>2</sup> matrix and NA = 3. All sequences underestimate the extent of fibrillation; however, the error was greater for the FLASH images. The asterisk denotes that the error is statistically larger compared with the DESS image obtained with equivalent section thickness ( $P < 0.05$ ).

detect and measure accurately the extent of cartilage damage. Because it can visualize cartilage directly, MRI has become an important imaging tool with great potential in monitoring disease progression and response to therapy. To become a practical tool in the development of therapy, MRI must accurately measure early damage, when these therapies are likely to be most effective.

Early cartilage degeneration in OA begins in the superficial layer as fibrillation (1). Although MRI has been shown to be accurate in assessing overall cartilage thickness (7,8) and more advanced focal defects (9), it is poor in demonstrating early fibrillation, which precedes significant cartilage loss (3–5,10). Relatively few studies have attempted to determine the cause of the poor diagnostic performance of MRI in diagnosing early forms of cartilage degeneration. Rubenstein et al (6) have described the limitation of resolution in identifying fibrillation and concluded that current clinical MR methods do not have adequate signal-to-noise ratio (SNR) to resolve fine fibrillation. This conclusion was supported by the results of Link and coworkers in their evaluation of spatial resolution. Although they were able to detect 91% of artificially produced cartilage lesions using a minimum voxel size of  $156 \times 312 \times 500 \mu\text{m}$ , accuracy in determination of lesion size and depth was less than 50% (11). The authors concluded that increasing spatial resolution improved diagnostic performance, but still limited assessment of lesion size and depth.

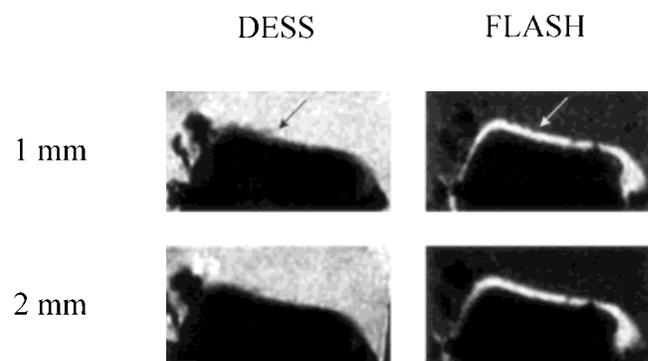
Results from this phantom study confirm findings of earlier clinical studies, demonstrating that MRI underestimates the extent of superficial fibrillation and grooves (3–5). Error in detection is pulse sequence dependent, with greater error observed with 3D fat-suppressed FLASH images. In contrast to the conclusions of Rubenstein et al (6), this finding is not a direct result of resolution, as negative bias persists when high-resolution FLASH images are obtained with equivalent SNR. At equivalent voxel resolution, the bulk SDNR is greater for the FLASH images. While adequate SNR is necessary for detection, our results indicate that contrast between cartilage and synovial fluid is an important additional source of error in identifying and determining the extent of superficial fibrillation.

This study compares two standard 3D MR pulse sequences in detection of focal surface lesions in the presence of overlying fluid. The parameters used in the 3D fat-suppressed FLASH, and DESS sequences were previously validated in the assessment of normal cartilage volume (12). The FLASH sequence provides T1-weighting with radiofrequency (RF) spoiling of the transverse magnetization. The addition of chemical shift fat saturation increases the contrast of cartilage to synovial fat and bone marrow. The DESS sequence is a hybrid steady-state gradient-echo sequence designed to increase contrast between fluid and cartilage by combining images made from the first and second gradient-echo signals. The theory and application of the DESS sequence in cartilage imaging have been previously reviewed (13) and compared with turbo spin-echo T2-weighted images in detection of surface lesions (14). Briefly, the initial gradient echo has mixed T1 and T2\* weighting, which provides high SNR but poor contrast

between cartilage and fluid. The image generated from the second echo signal has high T2\* contrast, but lower SNR. In the DESS image the signal from the individual echoes is averaged to generate a single image with improved contrast between cartilage and synovial fluid. Due to the T2\* contribution of the second echo in the DESS images, fluid is hyperintense to cartilage.

Previous studies have compared pulse sequences to determine accuracy and reproducibility in the measurement of cartilage thickness (12,15), volume (16), and identification of focal lesions (17–21). Additional studies compared relative accuracy of 2D vs 3D sequences (22,23). There is general consensus that 3D fat-suppressed spoiled gradient-echo sequences provide the greatest accuracy in both lesion detection and determination of cartilage volume. However, previous studies determining optimal pulse sequences for lesion detection have generally included more severe lesions in which there was greater than 50% loss of cartilage. The apparent discrepancy between our results and prior studies demonstrating greater accuracy of the spoiled gradient-echo (FLASH) technique reflects differences in degree of cartilage damage, as well as the influence of contrast between cartilage and fluid.

In both phantom and patient studies, FLASH images provided greater SDNR between cartilage and fluid. Using the fat-suppressed 3D FLASH sequence the in vivo SDNR of  $7.3 \pm 1.8$  is lower than previously reported by Recht et al (21), and Disler et al (24) reflecting the lower B0 field strength used in this study. Both DESS and fat-suppressed FLASH images had similar SDNR for human and phantom studies, indicating that the phantoms are representative of the magnitude of in vivo contrast. Figure 2 is representative of phantom images obtained in this study. With the DESS images, areas of abrasion are visible as low-intensity filling defects in hyperintense fluid. These fronds of abraded cartilage are inconspicuous on the fat-suppressed FLASH images despite the high contrast between fluid and the non-abraded cartilage. Given the greater SDNR of the FLASH images at equivalent voxel resolution, bulk tissue contrast does not explain the observed difference in bias. We postulate that the greater error reflects local surface



**Figure 2.** Representative DESS and FLASH images of porcine cartilage phantoms demonstrating area of superficial cartilage irregularity (arrow). On the DESS images, the fronds of abraded cartilage are visualized as hypointense filling defects within the fluid. Despite the high degree of contrast between fluid and bulk cartilage, the abraded fronds are less apparent on the T1-weighted FLASH images.

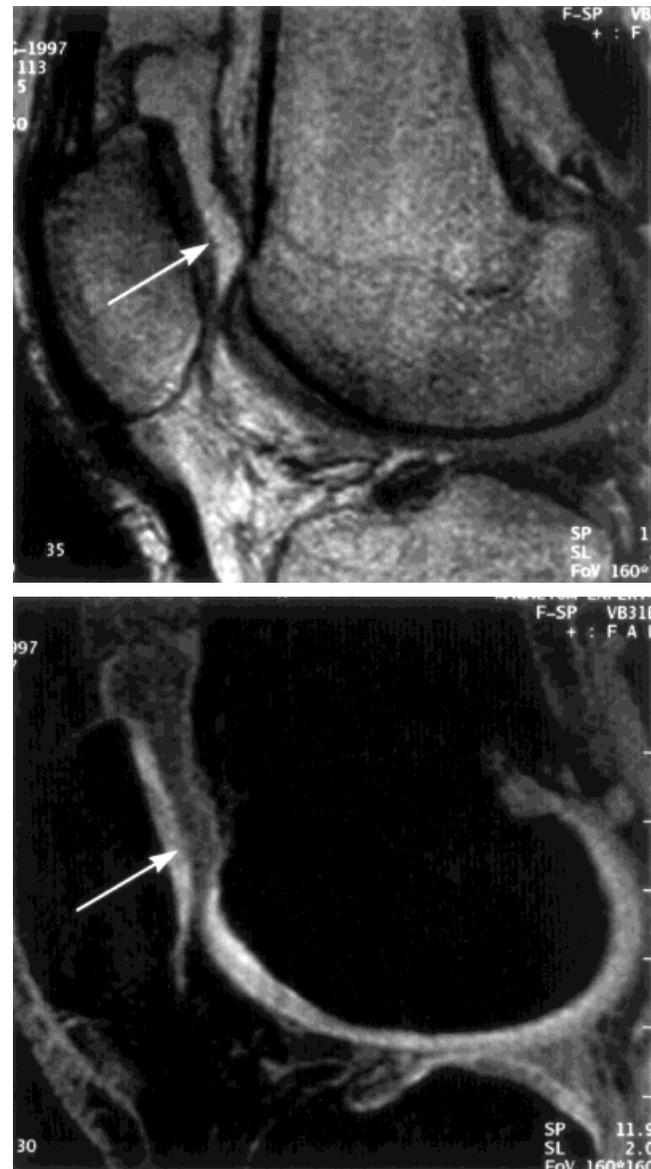
properties of fibrillated cartilage not represented in bulk tissue SDNR measurements. Specifically, we hypothesize that fibrillated cartilage provides efficient T2-shortening of exchangeable surface water, leading to greater lesion conspicuity on T2-weighted images.

In normal cartilage a large difference in T2 of cartilage [ $\sim 70$  msec (25)] and synovial fluid [ $\sim 535$  msec (26)] provides intrinsic T2 contrast at the articular interface. The cartilage surface contains a thin layer of type II collagen fibers oriented parallel to the surface that provides efficient spin-spin relaxation, resulting in short T2 values, as well as T2 anisotropy (27,28). In collagen solutions, T2 relaxation times decrease linearly with protein concentration (29). Prior T2 diffusion (30) and magnetization transfer (31,32) studies of protein solutions indicate that significant chemical exchange occurs between bulk water and water bound to collagen providing an efficient relaxation mechanism. Abrasion and fibrillation of the articular surface is associated with uncovering and disorganization of the superficial collagen fibers (2). This increases the amount of exposed collagen fibers, providing additional adsorption sites for surface water, thereby enhancing T2 relaxation. It is therefore likely that fibrillation shortens the T2 of adsorbed surface water, and through chemical exchange the adjacent mobile water protons. The resultant T2 shortening decreases the intensity of the fronds of abraded cartilage, which affects contrast with surrounding fluid. In the case of fat-saturated FLASH images, in which fluid is hypointense, the effect of shortening the T2 of adsorbed water is to decrease contrast with bulk synovial fluid, making the fronds less conspicuous. However, in the DESS images, in which bulk fluid is bright, T2 shortening of adsorbed water increases contrast and thus provides greater conspicuity of the lesion.

Images from both sequences were better able to demonstrate small full-thickness holes compared with partial-thickness superficial lesions (grooves and fibrillation) of similar size. In the case of holes, lesion conspicuity is increased by the presence of free fluid in deeper layers of cartilage and probably reflects differences in bulk tissue SDNR rather than surface properties. For these lesions detection is less dependent upon identification of subtle surface irregularity.

These findings indicate that detection of surface fibrillation in the presence of a joint effusion will be lower with 3D fat-suppressed FLASH images compared with the T2\*-weighted 3D DESS. A clinical example is presented in Fig. 3 demonstrating superficial irregularity of the patellar cartilage in the knee of a 42-year-old woman with a clinical history of anterior knee pain and swelling. While discrete surface irregularity is identified on the DESS image, the abnormality is less apparent on the corresponding FLASH image.

In an attempt to identify factors that limit detection of early cartilage damage, this study was designed to evaluate the potential role of tissue contrast using excised cartilage phantoms. Several technical factors limit direct extrapolation of these results to routine clinical application. First, as this is a phantom study, detection rates are probably greater than those that would be measured in vivo due to lack of patient motion



**Figure 3.** 3D DESS (A) and 3D fat-suppressed FLASH (B) image of a 42-year-old woman with a clinical history of anterior knee pain and swelling. A focal site of superficial irregularity consistent with fibrillation is identified on the 3D DESS images (white arrow). On the corresponding FLASH image the surface appears indistinct, and the irregularity is inconspicuous.

artifact and blurring. Second, a 2 g/dl albumin solution was used to model normal synovial fluid. This is based on reports that total protein content in normal synovial fluid is approximately 2 g/dl with an albumin to globulin ratio of 20:1 (33). Although there is poor correlation with T2, the T1 of synovial fluid decreases linearly with increasing albumin concentration (34). In this study the agreement in SDNR between the phantom and in vivo images indicates that this solution reflects the degree of contrast observed in clinical studies. However, in the setting of trauma or synovitis the amount of protein can increase to 5–8 g/dl (33). In these pathologic settings, the elevated protein and blood degradation products could significantly alter the relaxation properties of fluid, which will alter the contrast between cartilage and fluid. Third, phantoms were prepared using surface

abrasion as a model for fibrillation. While both result in uncovering of surface collagen, fibrillation is associated with proteoglycan loss, which is unlikely to occur with abraded phantoms. It is unlikely that the presence of proteoglycans would have a significant T2 shortening effect on adsorbed water. Prior studies have shown that unlike collagen, chondroitin sulfate has no appreciable T2 shortening (29) or magnetization transfer effect (31) in solution. As this study evaluated surface lesions, these results are not applicable to detection of basal degeneration or early chondromalacia that may not involve the articular surface.

In conclusion, results of this study indicate that tissue contrast is a significant factor in the insensitivity of MRI for detection of superficial lesions. We hypothesize that surface properties of fibrillated cartilage contribute significantly to the insensitivity of short TE sequences in identification of fibrillation. In contrast to previous papers suggesting that T1-weighted spoiled gradient-echo imaging provides greater accuracy for lesion detection, our results indicate that in the presence of joint fluid T2\*-weighted imaging increases detection of superficial fibrillation.

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