MR is a useful and non-invasive tool to evaluate articular cartilage. With the continued implementation of 3.0T MR for clinical use and improvement of the RF coil and pulse sequence, a high signal-to-noise ratio has been achieved to facilitate the acquisition of high-spatial resolution images. In addition, the clinical application of new MR techniques, capable of detecting changes in the biochemical components of articular cartilage at a high sensitivity, have been progressing and are expected to be useful for the early diagnosis of cartilage degeneration.

**Morphological evaluation of articular cartilage**

Various pulse sequences are used for MR evaluation of articular cartilage. The most common acquisition method is fat-suppressed, proton density weighted imaging using a 2D fast spin echo (FSE) sequence.

**Recent Advances in Clinical MR of Articular Cartilage**

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Proton density weighted imaging is intermediate between T1- and T2-weighted imaging. Relatively high contrast can be obtained between the cartilage and joint fluid and also between the cartilage and subchondral bone, providing useful information for the evaluation of articular cartilage. Using fat suppression, joint fluid is visualized as a strong, high-intensity region while normal cancellous bone is visualized as a low-intensity region. This facilitates the sensitive detection of joint fluid in injured cartilage and the ability to detect fluid present between a delaminated osteochondral fragment and the bone marrow.

When using a relatively short bandwidth or large pixel size in the acquisition, the image of bone marrow fat overlaps the image of cartilage due to a chemical shift artifact, making cartilage evaluation difficult; however, overlapping of the bone marrow fat image can be inhibited using the fat suppression method. Since articular cartilage is thin and has a curved structure, making a diagnosis based on a single imaging plane may lead to overlooking a lesion or misidentifying an artifact as a lesion. It is necessary to confirm lesions in several imaging planes on evaluation using 2D acquisition.

To overcome these issues, a 3D acquisition is employed in which the volume of the entire articular cartilage is imaged and a specific cross-sectional plane is evaluated on a workstation using multi-planar reconstruction. Various pulse sequences have been used for 3D MR of articular cartilage, yet most of these employed anisotropic voxels, which often deteriorated the reformatted image from the original image and thus led to a non-diagnostic study. To address this situation, acquisitions using isotropic voxels have been attempted. The isotropic voxel imaging method currently used employs 3D gradient echo (GRE) sequences, such as balanced-steady-state free precession sequences.

The 3D Cube FSE sequence has recently been utilized at our institution for the evaluation of articular cartilage. The 3D Cube FSE method is capable of acquiring isotropic voxel T2-weighted or proton density weighted images using FSE. Generally there have been problems with a 3D FSE method, such as blurring artifacts produced with T2 decay or the effective TE prolongs when the echo train length is increased to shorten the acquisition time. Using the 3D Cube FSE sequence, images with high-spatial resolution and favorable contrast of soft tissue—

Figure 1. 3D isotropic MR images of the knee joint using the 3D Cube FSE method (0.7 x 0.7 x 0.7 mm). Sagittal plane, original image (A); transverse plane, reformat (B); coronal plane, reformat (C).
inhibiting blurring artifacts—can be acquired, even when a long echo train is used, by changing the flip angle (FA) of the refocus pulse (termed refocused flip angle modulation). In addition, the use of low FAs became possible, enabling the reduction of specific absorption rate (SAR).

It has been reported that the high contrast-to-noise ratio of articular cartilage and joint fluid can be obtained using the 3D Cube FSE method compared to five other new 3D MR methods for evaluating knee cartilage at 3.0T, while maintaining sensitivity, specificity, and accuracy equivalent to the conventional proton density weighted imaging. This suggests that the 3D Cube FSE method is very useful for the evaluation of articular cartilage.

In our examination of the technique, we added proton density weighted imaging using the 3D Cube FSE method to the conventional 2D acquisition as a routine protocol for the knee joint. Using a Discovery MR750 3.0T and an 8-channel phased-array knee coil, our 3D Cube FSE parameters are: TR, 2200 ms; TE, 24 ms; FOV, 150 x 150 mm; section thickness, 0.7 mm; matrix, 224 x 224.

The advantages of isotropic voxel imaging are the high spatial resolution, and possibly more importantly, the capability of reformatting the original image to a specific cross-sectional plane—such as sagittal, coronal, transverse, and oblique coronal sections, without deterioration (Figure 1). This is particularly useful for the evaluation of relatively small lesions in articular cartilage that have a thin, complex spatial structure. When Time Course evaluation is performed using common 2D imaging, the target region is not necessarily included in the slice in all examinations, making evaluation difficult. In 3D isotropic voxel imaging, the target region can always be evaluated in the identical cross-sectional plane by 3D collection of the entire articular cartilage, which is useful for Time Course evaluation.
Qualitative evaluation of articular cartilage

Articular cartilage abundantly contains a polar molecule, proteoglycan (PG), in a fine collagen fiber network. PG maintains a high swelling pressure of cartilage through interaction with water—another polar molecule—whereas the collagen fiber network maintains the cartilage morphology by resisting the swelling pressure. Articular cartilage is tolerant to mechanical loads due to this characteristic composition and structure, yet it has a poor healing ability as it lacks blood vessels and has low cell density. Degeneration of articular cartilage induces osteoarthritis (OA). Since no effective treatment is available for progressed OA other than surgery, it is desirable to diagnose articular cartilage degeneration as early as possible to initiate treatment that can prevent progression. In OA, cartilage degeneration accompanied by reduction of the PG content, irregular collagen arrangement, and an increase in the water content is observed from an early stage.

General routine MR is relatively sensitive in detecting morphological abnormality of articular cartilage, but it has been difficult to evaluate cartilage degeneration that occurs in an early stage of OA before the appearance of morphological abnormalities. New MR imaging techniques capable of the quantitative evaluation of changes in the composition and structure of cartilage, such as T2 mapping, have recently been clinically applied and are proving to be a useful qualitative evaluation method.

T2 mapping is an MR technique capable of evaluating the collagen arrangement and water content in cartilage, and it is useful for the detection of early-stage cartilage degeneration and quantitative evaluation of the severity of cartilage degeneration. Collagen is dense and regularly arranged, and the water content is mostly maintained at a constant level in normal cartilage; however, irregular arrangement and an increase in the water content of collagen progresses with cartilage degeneration. Since these changes prolong T2, T2 of cartilage prolongs with the progression of degeneration. In T2 mapping, T2-calculated images are prepared, and differences in the collagen arrangement and water content are quantified as differences in T2. T2-based color-coded images are visually evaluated in the clinical diagnosis and T2 measurement across a range of interest in a T2-calculated image is performed in detailed quantitative evaluation.

The Discovery MR750 is equipped with an application (CartiGram) for T2 mapping of articular cartilage and capable of preparing and analyzing color-coded T2 maps on a console or workstation. CartiGram employs the multi spin echo method optimized to reduce the influence of stimulated...
echo, facilitating T2 measurement with little error. Using CartiGram, we acquired images of the knee joint on the GE Discovery MR750 using an 8-channel phased-array knee coil under the following conditions: TR, 1,800 ms; TE, 11.5-92 ms; FOV, 140 x 140 mm; section thickness, 3.0 mm; matrix, 384 x 384. The time required for T2 mapping varies depending on the necessary spatial resolution—approximately eight minutes was necessary for our high-resolution acquisition.

T2 mapping is useful for the early diagnosis and quantitative evaluation of cartilage degeneration, yet several points are important for an accurate evaluation. It has been known that the water content and arrangement of the collagen network structure in the cartilage, which may be reflected in T2, may change according to location in the joint as well as layer in the cartilage. In addition to the variation of cartilage matrix composition in the joint, T2 of cartilage has been known to be sensitive to the relationship between the collagen network and orientation of the static magnetic field (B0) due to the orientation-dependent dipolar interaction. This is particularly the case when collagen fibers are oriented 54.7° relative to B0, which is termed the magic angle, as T2 is markedly prolonged on measurement at this angle. To avoid interpreting T2 prolongation due to the variation of cartilage matrix composition in the joint or the angle formed by collagen fibers and static magnetic field as cartilage degeneration, it is important to understand the regional differences of T2 in a specific joint.

**Conclusion**

Using a newly introduced clinical MR technique as discussed above in combination with the standard, routine MR, diverse and detailed information can be non-invasively collected, such as morphological changes in cartilage, the severity of cartilage degeneration, and location, range, and depth of lesions including the surrounding tissue. The importance of detailed MR diagnosis of the knee joint may increase with the advancement of preventive medicine for OA and progression of regenerative medical care techniques for cartilage injury.

**References**


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**Teikyo University Chiba Medical Center** is one of the leading university hospitals located in Chiba, Japan. The Advanced Diagnostic Imaging Center offers advanced diagnostics through the use of state-of-the-art imaging equipment.