Review Article

MR Imaging of Articular Hyaline Cartilage

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MR imaging is still an evolving technique for the diagnosis of joint cartilage lesions. Early morphologic changes in the degenerative cartilage are not reliably diagnosed even with use of tailored MR imaging techniques. The detection of the biochemical changes of cartilage or high-resolution MRI will serve as an important tool for the early diagnosis of cartilage degeneration in near future. Further prospective studies are needed to establish the role of MR imaging in clinical use.

Keywords: Hyaline cartilage; MR imaging; Joint; Microscopy coil

Introduction

Hyaline articular cartilage is a crucial tissue that permits a frictionless joint articulation, yet it is capable bearing enormous loads. Most of the cartilage lesions occur as a result of trauma or degeneration. The lesions may be clinically occult initially, but it can progress to osteoarthritis (OA) causing serious functional deterioration. Recent development of surgical and pharmacological techniques have enabled the treatment and prevention of cartilage damage, leading to increasing demand for the accurate assessment of lesions of the articular cartilage, both for the early diagnosis and subsequent monitoring after the therapy. Currently, arthroscopy is considered as a standard of reference in the diagnosis of cartilage lesions, but it is not suitable for frequent serial examinations to monitor the effect of therapy because of its invasiveness and expense.

Conventional radiography is widely used in evaluating the progression of OA based on joint space narrowing, subchondral sclerosis, subchondral cyst and osteophytes. Weight-bearing radiography demonstrates narrowing of the joint space associated with thinning of the cartilage in the femorotibial compartment, but it remains an indirect approach and is not sensitive for the detection of early lesions. CT arthrography demonstrates the cartilage abnormality, but the spatial resolution is limited in the articular surfaces parallel to the scanning plane.

MR imaging, by virtue of its superior soft-tissue contrast, multiplanar capabilities and ability to allow direct visualization of the cartilage, is superior to conventional imaging techniques for evaluation of the articular cartilage. Several pulse sequences are advocated for demonstration of the normal articular cartilage and cartilage lesions. However, the consensus has not been yet obtained with regard to the most appropriate sequence for evaluation of the articular cartilage. The strategy of MR imaging should be considered based not only on the research purpose but also on the clinical standpoints. In this commentary, the current status of MR imaging in the assessment of articular hyaline cartilage will be discussed.

Structure of normal articular hyaline cartilage

Hyaline cartilage consists of chondrocytes and a large extracellular matrix, composed primarily of water (75%) with electrolytes (mainly sodium), collagen II fibrils (20%) and highly negatively charged, osmotically active aggregates of proteoglycans (5%).

Depending on the different arrangement and orientation of the cellular component and the collagen framework, cartilage histology shows a zonal architecture (Figure 1): a superficial zone, transitional zone and a radial zone. In the tangential zone the collagen fibers are densely packed and oriented parallel to the articular surface, whereas in the transitional zone the collagen fibers have a random or oblique orientation. The radial zone represents the major part of the cartilage thickness with large collagen fibers oriented perpendicularly to the joint surface. The deepest part of the cartilage, adjacent to the subchondral bone, is partially calcified. The area that corresponds with the boundary between calcified and uncalcified cartilage is called "tidemark" region. The amount of water and proteoglycans differs among the cartilage layers, as water concentration is greater in the superficial zone.

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whereas proteoglycans concentration is greater in the transitional zone. High-resolution MR images can demonstrate these laminar structures (see Figures 4 and 5 on page xx), but there is some controversy on the total number of laminae and their appearance of MR1.

MR imaging techniques for the detection of morphologic abnormalities of the cartilage

The morphologic abnormalities of the cartilage vary from surface abnormalities, such as fibrillation or small focal defect, to full thickness defect. MR imaging techniques should be optimized to provide high spatial and contrast resolution images enough to detect early cartilage lesions. However, an experimental study by Rubenstein et al.7 showed that clinical MR images do not accurately reveal early degenerative changes in articular cartilage, because of insufficient spatial resolution and signal to noise ratio. In-plane resolution of 39 μm is required to exquisitely define degenerative changes in articular cartilage, and in-plane resolution of larger than 300 μm does not reliably show superficial alterations of articular cartilage. In-plane resolution of MR images used for the clinical study is usually 400-500 μm.

Despite this serious limitation, MR imaging has been used to evaluate the articular cartilage lesions, with varying success. The MR classification system to grade cartilage lesions, described by Yulisht et al.7 is based on the arthroscopic classification. Grade 1 corresponds to thickening and softening, without morphologic defect. Grade 2 involves superficial fissuring or fibrillation of the articular surface, or shallow ulceration or erosion composing less than 50% of the total thickness of the cartilage. Grade 3 is a partial-thickness defect of more than 50%, but less than 100%, of the cartilage thickness. A grade 3 lesion does not extend to the underlying bone, whereas a grade 4 lesion is a high-grade lesion with full-thickness cartilage defect extending to the underlying bone.

Currently, two MR imaging sequences are widely used in clinical studies: fat-suppressed 3D-spoiled gradient echo (3D-SPGR) sequence and T2-weighted or proton-density weighted fast spin echo (FSE) sequence with fat-suppression. On fat suppressed 3D-SPGR images, the articular cartilage appears as a high signal intensity structure relative to surrounding structures, and lesions in the cartilage most commonly appear as contour defects. On T2-weighted FSE images, the cartilage appears as a low homogeneous structure, providing an excellent arthrogram effect between cartilage and fluid through heavy T2 and MTC effects (Figure 2). It can detect not only contour defect but also signal abnormalities of the cartilage. Both techniques show similar sensitivity (46-95%) and specificity (97-100%).

The 3D-SPGR sequence has the benefit of thin slice thickness and capability of multiplanar reformation, but it is limited by a long acquisition time and typically relies on subsequent reconstruction from a single plane; the resolution of the reformatted images may not be sufficient for diagnosis of cartilage lesions. In addition, it is often difficult to distinguish the proliferated synovium from the cartilage. The FSE technique is limited by a thicker slice thickness, but multiple plane images are readily available because of a relatively short acquisition time (Figure 3). The combination of two planes offers sufficient coverage of articular surfaces to provide a high sensitivity and accuracy for cartilage defects. The FSE technique also offers better contrast between proliferated synovium and cartilage than the 3D-SPGR sequence. Using both techniques may enhance sensitivity in detecting the cartilage abnormality, but it should

Figure 1. Schematic drawing of the zonal architecture of hyaline cartilage, which is described by the predominant alignment of the collagen fibers. S=superficial zone; T=transitional zone; R= radial zone; TM= tide mark; C=calcified cartilage; SB=subchondral bony plate

Figure 2. A conventional T2-weighted sagittal image of normal cartilage of the knee joint. Hyaline cartilage is demonstrated as low signal intensity structure (arrows), which is contrasted by adjacent joint fluid showing high signal intensity.
be noted that both techniques still have limitation for the detection of early cartilage lesions.

**Evaluation of lesions of the cartilage at low field strength units (0.5 T or less)**

A few clinical studies have shown the validity of low field strength units in the assessment of articular cartilage lesions in the knee. The main limitation of low field strength units is poor signal to noise ratio, which has to be compensated for by increasing the section thickness, reducing the in-plane resolution and increasing the acquisition time. Moreover, the use of fat-suppression technique, which is used to increase the dynamic range and to suppress the chemical shift artifact, is not available, because the fat and water peaks are too close. In the experimental evaluation by Woertler et al.\(^\text{5}\) low field unit demonstrated significantly poor diagnostic performance than the high-field unit for the detection of cartilage defects.

We studied the efficacy of T2-weighted FSE sequence without fat-suppression in the detection of articular cartilage abnormalities of the knee on a 0.5 MR unit; the overall sensitivity and specificity in detecting cartilage abnormalities were 60.5% and 93.7%, respectively.\(^\text{6}\) MR imaging was more sensitive to the higher grade lesions: 31.8% in grade 1, 72.4% in grade 2, 93.5% grade 3 and 100% in grade 4. It was concluded that FSE sequence with use of a 0.5 T MR unit was less sensitive to mild cartilage abnormality, but useful in detecting moderate to severe abnormality of the articular cartilage.\(^\text{6}\) Drape et al.\(^\text{7}\) evaluated the validity of quantification of cartilage lesions in osteoarthritic knees with use of 0.2 T dedicated MR unit and concluded that quantification of cartilage lesions with MR imaging was well correlated with arthroscopic evaluation.

**Detection of biochemical or structural abnormalities of the cartilage**

Detection of biochemical or structural abnormalities of the cartilage, which precedes morphologic changes, will be essential in the diagnosis of the early cartilage degeneration. In degenerative process of cartilage, the loss of proteoglycans and collagen degradation occur with associated increase of water content and altered mobility of water protons. These biochemical changes can be assessed with measurement of T2\(^\text{17,18}\) or diffusion-weighted technique.\(^\text{19}\) Ionic contrast agents (e.g. Gd-DTPA), which are administered with either intra-articular or intravenous route, concentrate in the area of decreased proteoglycan and may prove useful in the diagnosis of early cartilage degeneration.\(^\text{20,21}\) Other approaches, which include using ultrashort echo times to assess the short T2 component of articular cartilage,\(^\text{22}\) spectroscopic imaging,\(^\text{23}\) and sodium MR imaging,\(^\text{24}\) are also under investigation. Each technique offers different information on the biochemical changes in cartilage and will serve as an important tool for the early diagnosis of cartilage degeneration in near future.

**Bone marrow abnormalities associated with cartilage damage**

Subchondral bone abnormalities have been demonstrated on MR images of OA. This MRI feature presents as areas of high signal intensity with ill-defined margins on fat-suppressed T2-weighted or on STIR images. The finding is commonly referred to as "bone marrow edema", but its exact cause is still unknown. Possibilities include pulsion of joint fluid into the marrow space through defects in the articular surface, inflammation in reaction to cartilage breakdown products or other factors in intruded joint fluid, or microtraumatic changes associated with mechanical overloading.\(^\text{25}\) Recently, it has been shown that bone marrow abnormality in patients with knee OA is associated with pain\(^\text{26}\) and is predictive of progression of joint damage, as evidenced by articular cartilage loss assessed by radiography.\(^\text{27}\) Garnero et al.\(^\text{28}\) demonstrated that bone marrow abnormalities on MRI is associated with elevated urinary excretion of C-terminal crosslinking telopeptide of type II collagen (CTX-II) that has recently been shown to be a predictor of progression of OA.

**High-resolution MR images with 3.0 T MRI or microscopy coil**

MR imaging of the cartilage at 3.0 T offers increased S/N ratio, higher spatial resolution, or shorter imaging time relative to MR imaging at 1.5 T. It can therefore provide superior ability to detect changes in cartilage lesions with increased accuracy.\(^\text{29-31}\)

Recently high-resolution small MRI coil (microscopy coil) can be utilized in clinically available 1.5 T scanners to investigate microanatomy of the joint structures.\(^\text{32}\) It can provide high-resolution images of articular hyaline cartilage, demonstrating a laminar pattern.

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**Figure 3.** Hyaline cartilage injury. A T2-weighted sagittal image shows a defect of the cartilage in the medial femoral condyle (arrows).
corresponding to the histological zonal architecture (Figures 4 and 5). This technique can be useful in demonstrating early cartilage lesions, but the limitation is that the coil is only applied to the small joints or superficial joint structures that include the temporomandibular joint, wrist, hand, foot, elbow or patellofemoral joint (Figure 6).

**What is the clinical role of MR imaging?**

Although many studies have evaluated the ability of MR imaging in the detection of cartilage abnormalities, the clinical role of MR imaging have not been yet established. In fact, some studies on MR imaging of joint cartilage have reported negative diagnostic outcome in clinical use. The clinical role of MR imaging depends on various factors, such as history, signs and symptoms of the patients, radiographic findings, and treatment protocols.

One of the purposes of MR imaging is to find a symptomatic cartilage lesion. Cartilage lesions are often noted at arthroscopy in the painful knees. However, it is difficult to determine whether the cartilage lesions are related with symptoms or not. Several studies
showed that mesimal tears are seen in a relatively high prevalence in an asymptomatic population, but the prevalence of cartilage lesions in an asymptomatic population is not yet known. As mentioned previously, bone marrow abnormality associated with cartilage lesions could be one of the findings suggesting a symptomatic cartilage lesion on MR imaging. The presence of cartilage lesions should be carefully interpreted with other clinical information, such as the history and physical examinations, especially in the process of surgical decision-making.

The surgical techniques for the repair of cartilage lesions include drilling, abrasion and microfracture: the procedures to stimulate cartilage repair with fibrocartilage. Recently, transplantation techniques have gained widespread use and interest. As low-grade cartilage defects are not usually treated surgically, inability to detect early cartilage lesions with MR imaging is not a great disadvantage. Thus, one of the major roles of MR imaging for preoperative assessment is to determine the size and location of full-thickness defect of the cartilage (Figure 3). However, the use of MR imaging for assessment of postoperative course has not been fully evaluated.

It is likely that fibrocartilaginous repair tissue have different MR appearance from that of normal cartilage. Further studies are needed to determine the appearance of repair cartilage in patients undergoing various therapies.

MR imaging also can be a useful tool in monitoring the outcome of various medical treatment of arthritis. Quantitative analyses by measurement of T2 value or cartilage volume have been tried for this purpose, but future longitudinal studies are still needed to establish its clinical role.

References
