MR Imaging Tools to Assess Cartilage and Joint Structures

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Introduction

Standing radiographs provide important information regarding angular deformities and weight-bearing alignment of the joints, but provide only indirect information about joint integrity. Given its superior soft tissue contrast and direct multiplanar acquisition with the ability to accurately assess the complex geometry of various joints, magnetic resonance imaging (MRI) is a highly suitable tool by which to assess osteoarthritis (OA).

Magnetic Resonance Imaging of Cartilage

Cartilage is a soft, viscoelastic tissue with strong imaging and anisotropic mechanical properties. The MRI signal properties are dependent on the cellular composition of collagen, proteoglycan, and water, but also the MR pulse sequence utilized. Several standardized pulse sequences are available that have been assessed for accuracy and reproducibility based on a suitable surgical standard [14]. 3D modeling of joint structures is now available with the use of standardized fat-suppressed gradient echo or 3D fast spin echo techniques, which when applied with isotropic voxels, are amenable to semiautomatic segmentation algorithms and volumetric quantification of cartilage. However, cartilage volume is a function of both surface area and thickness; longitudinal changes are affected by alteration in thickness, such as swelling in the presence of proteoglycan loss in early OA and alterations in surface area, such as the

development of osteophytes. For this reason, geographic regional assessment of cartilage thickness is generally more useful than overall assessment of cartilage volume.

Normal cartilage also demonstrates “gray-scale stratification,” with lower signal intensity closer to the tidemark and subchondral plate and higher signal intensity in the transitional zone, related largely to collagen orientation in the extracellular matrix. Loss of normal gray-scale stratification is an important clinical feature that may herald subsequent delamination of cartilage from the subchondral bone. It is also important to assess the global joint, inclusive of the menisci, subchondral bone, synovium, and ligaments. More rapid progression of OA is typically associated with a combination of factors yielding to loss of structural integrity of the entire joint (Fig. 1).

Magnetic Resonance Imaging and Osteoarthritis

OA commonly results in turnover of subchondral bone with sclerosis and varying amounts of bone marrow edema. Severe and disproportionate edema patterns should raise scrutiny for the presence of a focal subchondral fracture, which may serve as a precursor to the development of osteonecrosis (Fig. 2).

Several scoring systems have been devised for assessment of cartilage morphology. The most comprehensive scores involve assessment not just of cartilage thickness and loss but also of the integrity of the ligaments, menisci, and synovium. Several modifications have been suggested due to the sometimes cumbersome application of scoring systems in clinical trials. For example, the WOMS score divides osteophytes into a range of 0 to 7 [13]. Modifications have been suggested [8]. These scoring systems allow for identification of MR features associated with more rapid progression of OA, including more advanced radiographic disease at the time of the initial evaluation [4], high baseline BMI [2, 17], baseline meniscal tear or extrusion [17], or progressive bone marrow edema [7, 12, 16].

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Fig. 1. A 21-year-old professional basketball player with a chronic valgus insufficient knee. **a** Coronal fast spin echo image demonstrates chronic deficiency of the medial collateral ligament (*arrow*). **b** On the initial MRI, focal loss of gray-scale stratification was noted on the corresponding fast spin echo image of the tibia (*arrow*). **c** Subsequent MRI obtained 7 months later demonstrated complete cartilage delamination, which was considered “at risk” on the study performed 7 months earlier

While these tools are established, important technical challenges remain, especially when planning multicenter cartilage repair trials. Standardization of field strength, imaging coils, and MR protocols is essential. Sufficient spatial resolution is important to detect partial thickness lesions, abnormal synovium, and subchondral sclerosis. Increased magnetic field strength results in an increased signal to noise ratio, but comes with increasing artifacts and safety issues. Most importantly, the choice of cartilage pulse sequence should use a series of parameters that have been independently validated, assessed for accuracy, and published in the literature.

MRI and Tissue Biochemistry

While these measures provide an effective means by which to assess joint morphology, they provide only indirect assessment of cartilage biology. The more recent development of quantitative MR techniques has provided indirect insight into tissue biochemistry. To assess cartilage proteoglycan or glycosaminoglycans (GAG), several techniques are available, including sodium MRI, performed at 3 or 7 T [6], delayed gadolinium enhanced MRI of cartilage (dGEMRIC) [21], and T1 rho imaging [20]. To assess cartilage orientation, quantitative T2 mapping is most often utilized, but may also be explored using the less commonly performed diffusion tensor weighted imaging [1, 9, 22]. To apply these MR techniques in a longitudinal fashion,

Fig. 2. Sagittal fast spin echo image demonstrates a focal subchondral fracture (*arrow*) surrounded by intense bone marrow edema pattern, a patient with early OA that has undergone partial medial meniscectomy

registration of the quantitative MR data to morphologic imaging is important so as to provide reasonable correlation of anatomic regions of the joint over time.

These quantitative MR techniques are suitable for studying populations at risk for development of progressive or early OA, such as developmental dysplasia or femoroacetabular impingement in the hip or patellofemoral overload in the knee (Fig. 3). Kim et al. used dGEMRIC techniques to study a cohort of patients with developmental dysplasia treated with osteotomy and showed that patients who clinically failed osteotomy had lower dGEMRIC indices of GAG content; in fact, the dGEMRIC index was more predictive of failure than radiographs alone [3, 10].

Traumatic models of OA have also been studied, and recent data suggest that 100% of patients sustain chondral damage at the time of pivot shift following initial anterior cruciate ligament (ACL) tear, with an increase in cartilage degradation at longitudinal follow-up, particularly after 5 years [15]. The transchondral fracture associated with a pivot shift results in compression over the lateral femoral condyle and shear over the plateau, yielding variable degrees of cartilage loss. Tiderius et al. studied a small cohort of patients following acute ACL injury using dGEMRIC and noted a loss in GAG in both medial and lateral femorotibial surfaces, suggesting that the trauma had a negative effect on cartilage homeostasis, resulting in depletion of

Fig. 3. **a** Coronal fast spin echo image of a patient with developmental hip dysplasia demonstrates intact cartilage morphology but prolongation of both T1rho (**b**) and T2 mapping (**c**), indicative of matrix depletion in the setting of early OA

matrix in areas that were not initially affected by the transchondral fracture sustained at pivot shift [18]. Li et al. also studied ACL injured patients, showing significant prolongation of T1 rho over the medial compartment and the lateral tibial plateau [11].

Following cartilage repair, these quantitative MR techniques may provide insight into repair tissue ultrastructure, providing an important noninvasive means by which to assess tissue biochemistry and obviate the need for post-repair biopsy [5, 19].

Summary

A combination of both morphologic and quantitative MR provides objective data to assess not only cartilage morphology but also cartilage biochemistry, inclusive of proteoglycan content and collagen orientation. Challenges still exist, however, as these quantitative techniques increase scan time, are not universally available across sites, and are sometimes restricted to higher magnetic field strengths of 3 T. Standardization of post-processing algorithms and registration software are important to provide more uniform data in multicenter trials. Several ongoing longitudinal registries are being established to study populations at risk, and these preliminary studies will provide important information suitable for powering studies aimed at assessing potential pharmaceutical intervention to delay the progression of OA. In addition, these MR data provide important insight into the appropriate timing of surgical treatments aimed at delaying progression and provide noninvasive and objective assessment of cartilage repair techniques.

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