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Quantitative Magnetic Resonance Imaging of Cartilage Resurfacing Procedures

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Recent advances in imaging technology have provided clinicians with multiple options for the evaluation of patients after cartilage resurfacing procedures. These methods, primarily performed with magnetic resonance imaging, provide a noninvasive assessment of cartilage health. Novel imaging sequences can evaluate the structure of the collagen network and biochemical composition of the repair tissue, among other properties. Quantitative imaging, including $T_1\rho$, T_2 T_2 star, diffusion-weighted imaging, and sodium imaging, has the potential to replace second-look arthroscopy as the gold standard for a longitudinal assessment after cartilage resurfacing. Multiple clinical studies have employed these methods after various resurfacing methods, with promising early results. The purpose of this article is to review multiple different imaging methods for quantitative evaluation of cartilage, including advantages and disadvantages of these techniques and an overview of preclinical and clinical studies of quantitative imaging after cartilage resurfacing.
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Introduction

The clinical evaluation of a patient following a cartilage restoration procedure is often challenging. The physical examination may not provide much information regarding the recovery process. Conventional imaging modalities, such as radiography, computed tomography (CT), and magnetic resonance imaging (MRI), are difficult to interpret, with postoperative changes often appearing similar to otherwise concerning findings. Although the previous gold standard for the in vivo postoperative evaluation of cartilage restoration procedures was a second-look arthroscopy, recent advances in quantitative imaging allow for a more comprehensive, noninvasive evaluation of cartilage changes.[1,2] These modalities, summarized in the Table, provide surgeons with powerful information and may help guide rehabilitation and further treatment. In this article, we review the current options for quantitative cartilage imaging as well as the feasibility of using these imaging techniques to assess cartilage health following repair.

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Current Quantitative Imaging Modalities

MRI Scoring Systems

Standard clinical imaging sequences may be used with reproducible joint scoring systems to systematically quantify changes after cartilage repair. MR-based scoring systems have been used to evaluate patients after cartilage repair, with the most common system being the magnetic resonance observation of cartilage repair tissue.[3] This system uses standard clinical MR sequences to evaluate multiple parameters after cartilage repair, including thickness, integration, adhesions, signal intensity, presence of an effusion, and other parameters. This system affords high interuser and intrauser reliability for both surgeons and radiologists, though does not use the full potential of MR sequences to evaluate articular cartilage.[3]

Delayed Gadolinium-Enhanced MRI of Cartilage

Gadolinium, a commonly used exogenous contrast agent for MRI, is a chelated ion used in multiple forms of MRI. The

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Table Advantages and Limitations of Quantitative Imaging Modalities

Imaging Modality	Information Provided	Advantages	Limitations
dGEMRIC	Glycosaminoglycan concentration	Direct assessment of glycosaminoglycan concentration	Need for contrast administration
$T_1\rho$	Glycosaminoglycan concentration	Reproducible assessment of biochemical composition No exogenous contrast needed	Potential for energy deposition in tissue
T_2	Integrity of collagen network Concentration of collagen Water concentration	Structural and biochemical assessment No exogenous contrast	Signal effected by alignment of cartilage relative to magnetic field
T_2 star	Collagen structure or content Water content	Structural assessment of cartilage No exogenous contrast 3-D acquisition Fast scan time	Signal effected by alignment of cartilage relative to magnetic field
Diffusion-weighted imaging	Integrity of collagen network	No exogenous contrast	Most sensitive to patient motion
	Proteoglycan concentration	Structural and biochemical assessment	Low signal-to-noise ratio
Sodium MRI	Proteoglycan concentration	No exogenous contrast Assessment of biochemical composition of cartilage	Low signal-to-noise ratio Requires specialized hardware
Contrast CT	Proteoglycan concentration	Signal directly proportional to proteoglycan contrast	Need for contrast administration Poor visualization of whole knee joint

molecule is a negatively charged ion, which is repelled by the negatively charged glycosaminoglycans (GAG) of articular cartilage. Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) involves the administration of gadolinium, followed by a delay before imaging, approximately 30-45 minutes.[4,5] During this time, the contrast agent diffuses into the articular cartilage and distributes in a pattern that is inversely correlated with proteoglycan content. This method has been used frequently in prior studies, given the ability to provide additional information regarding the molecular makeup of articular cartilage.[6-8] A clear disadvantage with dGEMRIC is the need for contrast agent administration. Gadolinium is associated with nephrogenic systemic fibrosis and should not be administered in the setting of a decreased creatinine clearance.[9]

$T_1\rho$ Magnetic Resonance Imaging

One common MR-based methodology with applicability to cartilage imaging is $T_1\rho$. This technique measures spin-lattice relaxation time in the rotating spatial frame.[10,11] Images are acquired at various echo times, and an exponential fit is used to determine the $T_1\rho$ relaxation time. The proteoglycan content of cartilage can be interrogated with $T_1\rho$ imaging (Fig. 1), owing to the negatively charged GAG. Histologic studies of animal cartilage and explanted human specimens have correlated the content of proteoglycan with the $T_1\rho$ relaxation times, with increasing values of $T_1\rho$ associated with decreased levels of proteoglycan.[12,13] Additional in vivo work has shown that significant changes are present regarding the $T_1\rho$ relaxation time in early osteoarthritis.[14] Owing to the need for a high signal-to-noise ratio and gradient strength, a field strength ≥ 1.5 T is required for adequate image acquisition. This sequence requires no contrast administration and be acquired with routine clinical sequences. Disadvantages of this method include the need for manual cartilage segmentation for quantification and the potential for high amounts of energy deposition within tissues.[11]

T_2 Magnetic Resonance Imaging

The T_2 relaxation is a second possible MRI sequence for quantitative cartilage evaluation (Fig. 1). Similar to $T_1\rho$, multiple images are acquired at various echo times, and the T_2 relaxation time is calculated as an exponential fit of the signal decay. T_2 appears to provide more information on the macrostructure of articular cartilage, specifically the collagen network.[15] There is also likely some contribution from increased water within the cartilage. Similar to $T_1\rho$, T_2 imaging can be conducted on clinical scanners and does not require an exogenous contrast agent. Disadvantages of this technique include the need for image postprocessing and segmentation. The T_2 relaxation time shows increased susceptibility to the alignment of the cartilage within the magnetic field.[15,16]

T_2 Star Magnetic Resonance Imaging

Quantitative T_2 MRI uses the relaxation constant to provide information about the interaction of water molecules and collagen in cartilage.[17] T_2 star (T_2*) MRI measures T_2 relaxation times; however, it uses a sequence that accounts for field inhomogeneity when inferring information of the

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