Cartilage injury and repair: assessment with magnetic resonance imaging
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ABSTRACT
Articular cartilage damage plays a major role in joint degeneration and dysfunction. Accurate assessment of the morphology and degree of cartilage wear is important in diagnosis, prognosis and management, particularly as many of these patients are young or participate in high-performance sports. Magnetic resonance imaging is able to directly evaluate such injuries, due to its high spatial resolution and excellent soft-tissue contrast resolution. This pictorial essay aims to demonstrate normal and damaged articular cartilage on MR imaging, as well as surgically-repaired cartilage.

Keywords: articular cartilage, cartilage damage, cartilage repair, magnetic resonance imaging

INTRODUCTION
All synovial joints in the body have hyaline cartilage lining the articular margins, which play a crucial role in proper joint function. Hyaline cartilage has two unique properties which serve this purpose: it is able to sustain loads of up to ten times body weight during daily activities such as walking, and is near-frictionless with an extremely low coefficient of friction. It is continually synthesised and repaired to replace damage from mechanical wear, and is able to last for up to seven or eight decades.

Failure of normal cartilage function is a basic factor in the pathophysiology of osteoarthritis. Osteoarthritis is the most common form of arthritis, and its incidence and prevalence have been shown to increase by two to ten-fold from 30 to 65 years of age. Radiography has traditionally been used in evaluation of osteoarthritis, however, actual cartilage loss is indirectly assessed by the reduction in joint space. In addition, technical differences in positioning make accurate reproducibility difficult, and this form of measurement has been shown to be imprecise. With its ability to perform multiplanar imaging and excellent soft tissue contrast resolution, coupled with advances in pulse sequence development, magnetic resonance (MR) imaging has been used to evaluate cartilage morphology and integrity.

CARTILAGE STRUCTURE AND ANATOMY
Articular cartilage has a unique combination of porous, viscous and elastic properties which allow it to perform its functions. Although the term “hyaline” describes its amorphous appearance on light microscopy, it is actually highly fibrous. It is useful to conceptualise cartilage as a collagenous lattice, within which exist smaller water molecules and larger proteoglycan macromolecules. The collagen lattice has a differential structure within it, and can be divided into four zones or layers depending on the chondrocyte morphology and orientation, as well as the histological staining properties.

The deepest layer of cartilage is calcified, and serves to anchor the collagen lattice on to the underlying bone. This is separated from the next layer by a tide mark. The collagen fibrils within the next layer lie predominantly in a vertical (perpendicular to the cartilage surface) orientation, and this layer is known as the radial zone. The transitional zone above this has a more random orientation to the collagen fibrils, many of which lie in an oblique plane, to withstand shear forces. The most superficial layer consists of many collagen fibrils in a tangential (parallel to the cartilage surface) orientation, forming a thin layer of closely-packed horizontal leaves.

The proteoglycan macromolecules within the lattice draws water into the cartilage substance by osmosis. In the normal physiological state, the stiff collagen lattice prevents maximal uptake of water. This acts to distend the collagen lattice and keeps the fibrils under tension. This “inflated” state produces the compressive stiffness of cartilage and allows it to sustain loading. When there is disruption of the superficial layer from trauma or degeneration,
the surface fibrillation allows increased permeability of water, which is attracted into the cartilage from synovial fluid from the exposed negative charge of the macromolecules. This increase in the hydration of the cartilage, together with fragmentation of the macromolecules, renders the cartilage susceptible to mechanical stress and reduces its weight-bearing capacity. More load is then transferred to the subchondral bone, which responds by increasing bone deposition, and which then manifests as sclerosis.

NORMAL CARTILAGE APPEARANCE AND MR IMAGING SEQUENCES

The objective of MR imaging of cartilage is to evaluate surface integrity, cartilage thickness, matrix signal and subchondral margin and attachment to bone (Figs. 2a & b). The laminar appearance on histological specimens has been difficult to reproduce on clinical MR imaging, with best results ex-vivo, which were able to show a trilaminar appearance and accurate measurements of cartilage thickness.\(^8\,9\)

Grading of articular cartilage damage and ulceration is based on a modified Outerbridge classification system, where grade 0 is normal intact cartilage, grade 1 is chondral softening and blistering, grade 2 is a partial-thickness (less than 50%) defect or fissuring, grade 3 is a deeper (more than 50%) partial-thickness defect, and grade 4 is full-thickness cartilage loss with exposure of the subchondral bone.\(^10\) (Figs. 3a-d). Early changes manifest as surface fibrillation, which at arthroscopy show a typical “crab-meat” appearance (Fig. 4). Focal areas of sharply-marginated cartilage loss are likely to be due to shear or impaction injuries from recent trauma, whereas diffuse or larger areas of cartilage loss may be a result of chronic trauma or degeneration (Figs. 5-8). Cartilage delamination (Figs. 9a-c) and osteochondral lesions (Fig. 10) can also be evaluated with MR imaging.

Conventional T1-weighted and T2-weighted spin echo sequences are generally not able to evaluate cartilage signal and thickness well. T1-weighted images are relatively poor at demonstrating the cartilage-joint fluid interface, while on T2-weighted images, the deeper layers of cartilage merge with the subchondral bone, with the interface not being well discerned.\(^11\,12\) (Figs. 11a & b). Routine MR imaging without dedicated cartilage-specific sequences has a low (30% to 40%) sensitivity for cartilage defects in the knee.\(^13\)

The International Cartilage Repair Society (ICRS) formed an articular cartilage imaging
Fig. 3 Axial fast spin-echo proton-density MR images show varying degrees of articular cartilage wear at lateral facet of patella in different patients, illustrating the modified Outerbridge classification. Black arrows indicate site of cartilage abnormality.

(a) Increased focal areas of signal intensity within normal-thickness cartilage indicative of matrix damage and increased fluid content.
(b) Partial-thickness cartilage loss with surface fibrillation, affecting less than 50% of the cartilage thickness.
(c) Greater degree of cartilage loss (more than 50% of thickness) but without exposure of subchondral bone. Underlying early sclerosis seen in subchondral bone immediately deep to the area of cartilage loss.
(d) Complete cartilage loss with reactive sclerotic changes in the subchondral bone, indicating increased loading.

Fig. 4 Sagittal fast spin-echo proton-density MR image shows surface fibrillation on a focal area of the patellar articular cartilage (black arrow). The opposing trochlear cartilage is normal.

Fig. 5 Coronal fast spin-echo proton-density MR image shows a focal full-thickness defect in the articular cartilage over the lateral tibial plateau.
In 1998, a committee was established with the main objective to develop an internationally-acceptable imaging protocol for optimal evaluation of cartilage. The committee released its recommendations in January 2000, with the two most widely available techniques being the fat-suppressed 3-dimensional spoiled gradient echo (3D-SPGR) sequence and proton-density weighted fast spin-echo (FSE) sequences (Fig. 12a & b). Both techniques have been validated in patients at 1.0 and 1.5 Tesla field strengths. Published results for both techniques in the knee have been excellent, with sensitivities from 86-95%, specificities from 88-97%, accuracy from 83-92%, positive predictive values from 80-85% and negative predictive values from 91-97%, taking arthroscopy as the gold standard [6,13,15].

Fig. 6: Sagittal fast spin-echo proton-density MR image shows extensive delamination of the trochlear articular cartilage (white arrow), with a free cartilage flap (black arrow).

Fig. 7: Sagittal fast spin-echo proton-density MR image shows partial-thickness cartilage loss on the posterior aspect of the lateral femoral condyle (long black arrow), and full-thickness loss in the posterior aspect of the lateral tibial plateau (short black arrow). The primary injury is an oblique tear through the posterior horn of the lateral meniscus (white arrow), resulting in increased loading on the cartilage surfaces.

Fig. 8: (a) Coronal fast spin-echo proton-density MR image shows extensive fibrillation in articular cartilage over lateral tibial plateau, manifested as areas of ill-defined increased signal intensity (black arrows). The opposing femoral articular cartilage is normal. (b) Sagittal fast spin-echo proton-density MR image in the same patient shows prior tear in the anterior horn of the lateral meniscus (white arrow) and subchondral bone changes in the lateral tibial plateau (black arrow).
The two techniques have different advantages and disadvantages. The fat-suppressed 3D-SPGR sequence allows for thinner sections, down to 1mm thickness, which provides better definition of surface morphology. The fast spin-echo sequence utilises the magnetisation transfer effect, which makes it more sensitive for demonstration of signal abnormalities within the cartilage substance, before morphological defects appear. Other advantages of the fast spin-echo sequence are better visualisation of other soft tissue structures such as menisci and ligaments, and it is also less prone to susceptibility artifacts, which may be an issue in the post-surgical joint. Newer MR imaging sequences such as steady-state free precession and driven equilibrium fourier transform techniques have been reported to be able to achieve higher signal-to-noise (SNR) ratios, allowing good contrast between cartilage and adjacent tissue\textsuperscript{(16,17)} (Fig. 13).

The knee joint is particularly suited for cartilage evaluation, as the patella has the thickest articular cartilage in the body, and validation of imaging techniques is correlated with knee arthroscopy, which is widely used. However, other joints, such as the shoulder, wrist, hip and ankle can also be evaluated with similar MR techniques\textsuperscript{(18)} (Fig. 14).

**CARTILAGE REPAIR IMAGING**

The impetus in development of cartilage-specific MR imaging sequences is largely due to the feasibility of surgical techniques for cartilage repair, which have become well-established in sports medicine and orthopaedic surgery. The three broad categories are local stimulation of cartilage growth (which
include microfracture, drilling or abrasion), autologous transplantation of cartilage with either osteochondral elements or chondrocyte implantation, and allograft osteochondral transplantation\(^{(19)}\). In addition, significant ligament or meniscal tears in the knee should also be addressed, otherwise the transplanted or regenerated cartilage will still be subject to the same forces which caused the breakdown in the first place.

The marrow stimulation techniques aim to release stem cells from the subchondral bone at the site of cartilage defect, which will differentiate into repair cartilage with time. With the microfracture technique, the repair cartilage is expected to be mostly fibrocartilage, rather than hyaline cartilage, and will be of different signal intensity\(^{(20)}\) (Fig. 15). In autologous chondrocyte implantation, cultured chondrocytes are secured within the cartilage defect with an overlying periosteal patch\(^{(21)}\). This repair cartilage has been shown to change in signal intensity with time, possibly reflecting a change in composition, which is usually a combination of

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Fig. 11 Axial (a) T1-W and (b) T2-W MR images of the patella in the same patient show suboptimal distinction of articular cartilage from subchondral bone layer.

Fig. 12 Sagittal MR images show normal articular cartilage over the patella and trochlea on (a) fast spin-echo proton-density image (grey layer) and on (b) fat-suppressed spoiled gradient echo image (white layer).
Fig. 13 Sagittal MR image obtained with the dual-excitation steady-state (DESS) sequence shows normal articular cartilage over the lateral femoral condyle (white arrows) and lateral tibial plateau (black arrow).

Fig. 14 Axial fast spin-echo proton-density MR image of the left shoulder shows normal articular cartilage over both the humeral head and glenoid process articular surfaces. The patient also has a tear in the subscapularis tendon (white arrow) with medial subluxation of the long head of the biceps tendon.

Fig. 15 Coronal fast spin-echo proton-density MR image shows repaired cartilage over the medial aspect of the lateral femoral condyle (black arrow), 4 years after a microfracture procedure was performed. The repair cartilage is of lower signal intensity and has some surface irregularity compared to the native articular cartilage. However, there is good fill of the defect with no subchondral bony changes.

Fig. 16 Sagittal fast spin-echo proton-density MR images (a) before and (b) 1 year after autologous chondrocyte implantation for a cartilage defect in the trochea (black arrows). There is complete fill of the defect by a hyaline-like repair cartilage, without delamination or underlying bony hypertrophy.

Fibrocartilage and hyaline-like articular cartilage (Fig. 16). In osteochondral transplants, either with allograft or autograft, the main issues are incorporation of the bone plug into the native bone, and creation of a flush articular surface between the repair and native cartilage.
FUTURE DIRECTIONS
The next step forward in cartilage imaging will go beyond just imaging of the cartilage morphology, and will be able to non-invasively assess cartilage biochemistry. Possible parameters to evaluate are water content or hydration, collagen orientation and macromolecule concentration. Collagen fibre orientation is related to T2 relaxation times in T2 mapping, and related to diffusivity and fractional anisotropy in diffusion tensor imaging. Delayed gadolinium-enhanced MR imaging has been able to evaluate glycosaminoglycan concentration in cartilage.

CONCLUSION
Morphological assessment of articular cartilage should be part of the routine MR imaging evaluation of joints, and in particular the knee. From a diagnostic perspective, MR imaging assessment of cartilage can be useful in evaluating common, mild-but-niggling sport-related conditions such as anterior knee pain, where it could help differentiate a cartilaginous aetiology of pain from other causes. MR imaging is valuable for detection of early cartilage injury or wear, before secondary osteoarthritis sets in, as well as in assessment of suitability and postoperative follow-up of surgical cartilage repair.

REFERENCES
**SINGAPORE MEDICAL COUNCIL CATEGORY 3B CME PROGRAMME**

**Multiple Choice Questions (Code SMJ 200601A)**

**Question 1:** With regard to articular cartilage assessment:

(a) Radiographs provide an indirect measurement of cartilage thickness.

(b) There is good reproducibility of radiographs taken at different times to allow for assessment of change.

(c) Conventional T1-weighted magnetic resonance (MR) images are not able to demonstrate the surface (cartilage-joint fluid interface) of articular cartilage well.

(d) Conventional T2-weighted MR images are not able to demonstrate the deep (cartilage-subchondral bone interface) of articular cartilage well.

**Question 2:** Regarding the structure of articular cartilage:

(a) It consists of both a collagenous lattice and proteoglycan molecules.

(b) The collagen fibres in the radial zone have a circular orientation.

(c) The collagen fibres in the superficial zone are oriented parallel to the cartilage surface.

(d) The proteoglycan molecules function to attract and retain water molecules within the collagen matrix.

**Question 3:** With regard to evaluation of the articular cartilage:

(a) MR imaging can evaluate both cartilage morphology and integrity.

(b) The patella has the thickest articular cartilage in the body.

(c) There are usually 4 zones or layers within articular cartilage, discernable at microscopy.

(d) The modified Outerbridge classification for articular cartilage damage has 4 grades, from zero to 3.

**Question 4:** Regarding MR imaging of articular cartilage:

(a) The 4-layered appearance on microscopy can be accurately reproduced on in-vivo MR imaging.

(b) An early sign of cartilage damage is surface fibrillation.

(c) Both fat-suppressed 3-dimensional spoiled gradient echo (3D-SPGR) sequence and proton-density weighted fast spin-echo (FSE) sequences have been validated for cartilage imaging.

(d) The proton-density weighted FSE sequence is more prone to susceptibility artefacts, which may be seen in the post-surgical state.

**Question 5:** Regarding cartilage repair techniques:

(a) These techniques include local stimulation, autologous cartilage transplantation and osteochondral transplantation.

(b) Microfracture is based on the differentiation of stem cells to form repair cartilage.

(c) Microfracture is usually expected to produce hyaline repair cartilage.

(d) Osteochondral transplants can be performed using either autografts or allografts.

**Doctor’s particulars:**

Name in full:___________________________________________________________________________________

MCR number:_____________________________________  Specialty:____________________________________

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**Submission instructions:**

**A. Using this answer form**

1. Photocopy this answer form.
2. Indicate your responses by marking the “True” or “False” box.
3. Fill in your professional particulars.
4. Post the answer form to the SMJ at 2 College Road, Singapore 169850.

**B. Electronic submission**

1. Log on at the SMJ website: URL <http://www.sma.org.sg/cme/smj> and select the appropriate set of questions.
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**Deadline for submission:** (January 2006 SMJ 3B CME programme): 12 noon, 25 February 2006

**Results:**

1. Answers will be published in the SMJ March 2006 issue.
2. The MCR numbers of successful candidates will be posted online at http://www.sma.org.sg/cme/smj by 20 March 2006.
3. All online submissions will receive an automatic email acknowledgment.
4. Passing mark is 60%. No mark will be deducted for incorrect answers.
5. The SMJ editorial office will submit the list of successful candidates to the Singapore Medical Council.