Musculoskeletal and Emergency Imaging

MR imaging of cartilage repair surgery of the knee

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ABSTRACT

Articular cartilage is a complex tissue with unique properties that are essential for normal joint function. Many processes can result in cartilage injury, ranging from acute trauma to degenerative processes. Articular cartilage lacks vascularity, and therefore most chondral defects do not heal spontaneously and may require surgical repair. A variety of cartilage repair techniques have been developed and include bone marrow stimulation (microfracture), osteochondral autograft transfer system (OATS) or osteochondral allograft transplantation, autologous chondrocyte implantation (ACI), matrix-assisted chondrocyte implantation (MACI), and other newer processed allograft cartilage techniques. Although arthroscopy has long been considered as the gold standard for evaluation of cartilage after cartilage repair, magnetic resonance (MR) imaging is a non-invasive method to assess the repair site and can be scored using Magnetic resonance Observation of Cartilage Repair Tissue (MOCART). MR also provides additional evaluation of the subchondral bone and for other potential causes of knee pain or internal derangement. Conventional MR can be used to evaluate the status of cartilage repair and potential complications. Compositional MR sequences can provide supplementary information about the biochemical contents of the reparative tissue. This article reviews the various types of cartilage repair surgeries and their postoperative MR imaging appearances.

1. Introduction

Cartilage pathology (chondrosis) is common and can be caused by acute or repetitive trauma or degenerative processes. Articular cartilage lacks vascularity, and therefore most osteochondral or chondral defects do not heal spontaneously and require surgical repair [1]. Traumatic cartilage defects are associated with development of accelerated osteoarthritis and significant morbidities [2]. There are several surgical techniques available to repair damaged articular cartilage [3,4]. The aim of surgical repair is symptom relief, restoration of joint function, and prevention of accelerated osteoarthritis. Although arthroscopy historically remains the gold standard for evaluation of the cartilage after surgical repair, MR imaging is an invaluable non-invasive tool to assess not only the repair site but also the cartilage-bone interface, adjacent subchondral bone, and for other potential causes of knee pain or superimposed internal derangement. This article discusses different cartilage repair surgical techniques, their postoperative MR imaging features, and potential complications.

2. Cartilage repair surgical techniques

2.1. Bone marrow stimulation (microfracture)

Several techniques, including abrasion arthroplasty, subchondral drilling, and microfracture, may be used to stimulate the growth of new fibrocartilage from marrow-derived stem cells. The rationale is to abrade or create a series of small holes in the subchondral bone beneath the cartilage defect, resulting in bleeding and clot formation in the cartilage defect to stimulate fibrocartilage repair [5].

Microfracture is the most commonly performed marrow stimulating procedure, which creates multiple holes in the subchondral bone, 3 to 4 mm apart, by manually using an awl or a pick (Fig. 1). Controversy exists over the reproducibility of this crude fracture technique of the subchondral plate. Newer techniques have been created with drills and smooth picks for making controlled, less traumatic holes.
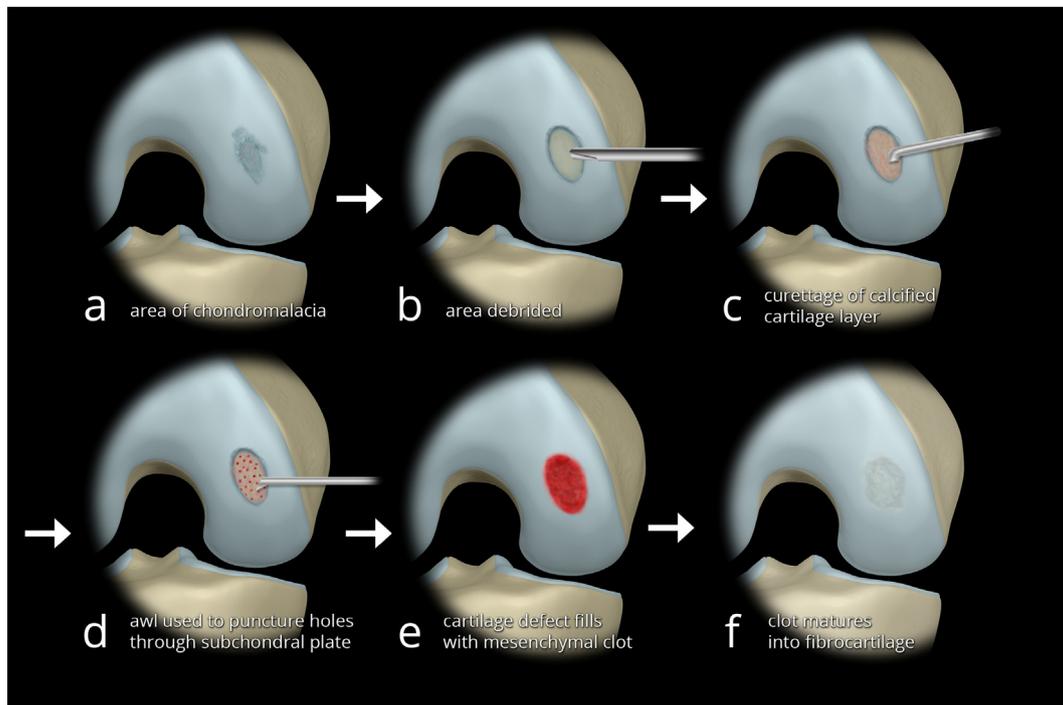
Microfracture is generally indicated for small osteochondral defects ($< 4\,cm^2$) but the outcomes generally become poor for larger lesions

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Fig. 1. Illustration of microfracture procedure. The area of chondromalacia (a) is debrided (b) and the calcified cartilage layer is curetted (c). An awl is then used to create multiple holes in the cartilage defect 3 to 4 mm apart (d). This results in bleeding and mesenchymal clot formation in the cartilage defect (e). The clot eventually matures into fibrocartilage (f).

[6,7]. Although patient age is not a specific contraindication, younger patients have significantly better clinical results than patients older than 40 years of age [8,9]. A low body-mass index is also associated with good clinical results [10,11]. The fibrocartilage tissue formed in the cartilage defect is less durable than the normal hyaline articular cartilage and therefore may deteriorate faster, affecting long-term clinical outcomes [11–13]. Mithoefer et al. demonstrated improved functional scores in patients who underwent a microfracture procedure for the first 2 years following microfracture, but there is some decrease in the International Knee Documentation Committee (IKDC) score after two years [10].

### 2.2. Mosaicplasty or osteochondral autograft transfer system (OATS)

Osteochondral autograft transplantation is also known as mosaicplasty. In this procedure, intact osteochondral tissue is harvested in the knee from a relatively non-weight-bearing site such as the lateral margin of the lateral trochlea or the region adjacent to the superolateral margin of the intercondylar notch. There are several commercial kits/tools for this procedure. The graft is then transferred to the cartilage defect (Fig. 2). The harvested osteochondral graft with its hyaline cartilage is more durable than fibrocartilage repair tissue generated by a microfracture procedure [14,15]. In a prospective study by Marcacci et al., 23 out of 30 patients (76.7%) had good clinical results at 7-year follow-up [16]. A meta-analysis study showed higher activity levels in patients with OATS than microfracture for osteochondral defect > 3 cm^2 [17]. Osteochondral autografts are less likely to cause graft rejection and have higher rates of graft incorporation than allografts. However, the disadvantage of autografts is the limited amount of donor cartilage that can be harvested, and associated morbidity at the donor site [18]. Large cartilage defects (> 4 cm^2) cannot be easily performed with OATS and are associated with risk of significant donor site morbidity [19]. One study showed that the failure rate is about 10% at 37-month follow-up, with affected patients requiring additional surgeries [20].
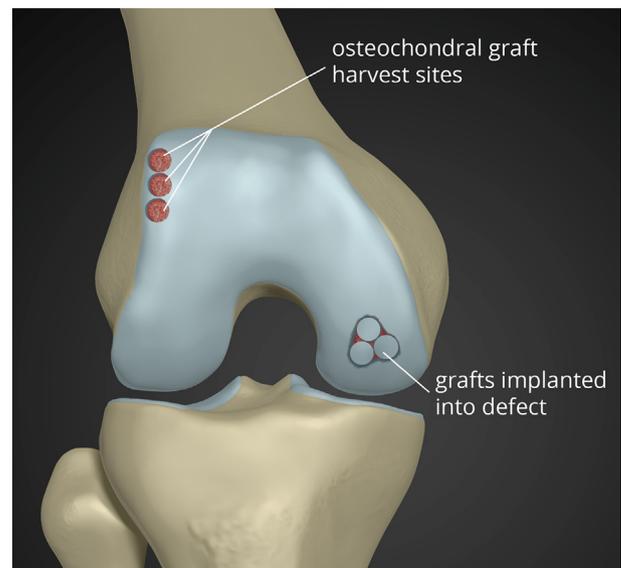
Fig. 2. Illustration of osteochondral autograft transfer system (OATS). Intact osteochondral grafts are harvested from a non-weight-bearing area and transferred to the cartilage defect site.

2.3. Osteochondral allograft transplantation surgery

A piece of bone and overlying cartilage are harvested from a freshly harvested (< 30 days) cadaver and are transplanted to the osteochondral defect. This procedure involves debriding the affected site to a subchondral depth of 6–8 mm [21]. The cadaveric allograft is obtained using a dowel technique for lesions < 10 cm^2 and a shell allograft technique for lesions larger than 10 cm^2 [22,23]. The graft is washed with pulsatile lavage and tailored to a matching shape. The graft is placed with press-fit fixation or utilizing bioabsorbable pins. This surgical technique is useful for repairing large defects (> 4 cm^2) given that
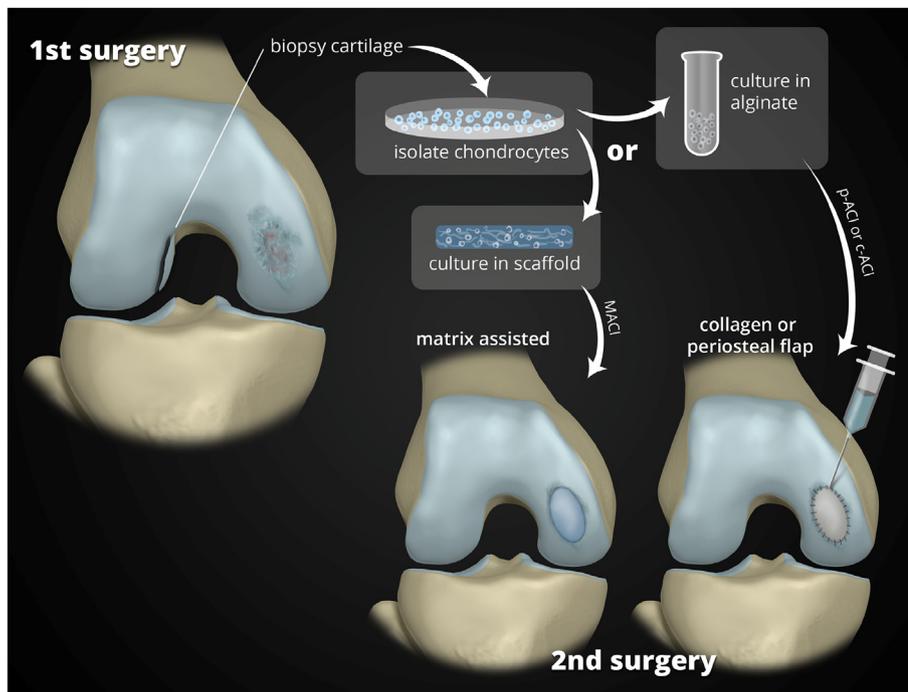
Fig. 3. Illustration of autologous chondrocyte implantation (ACI) and matrix-assisted chondrocyte implantation (MACI). Two stages are involved in both ACI and MACI. For ACI, during the first surgery, cartilage is biopsied, and chondrocytes are harvested from a non-weight-bearing site. The isolated chondrocytes are cultured in alginate medium. During the second surgery, a collagen or periosteal flap is sutured over the cartilage defect and then the cultured chondrocytes are injected beneath the flap. For MACI, similarly the chondrocytes are harvested from a non-weight-bearing site. The isolated chondrocytes are cultured in a type I/III scaffold collagen membrane, instead of alginate. In the second surgery, the membrane with seeded chondrocytes is implanted to the cartilage defect.

it has no limitation of donor-site availability or morbidity, making it particularly useful for osteochondritis dissecans (OCD), avascular necrosis (AVN), and trauma, in addition to large degenerative defects [24]. A prospective study by Krych et al. showed 38 of 43 (88%) athletes had limited return to sport, with 34 of 43 (79%) athletes back to the preinjury level after osteochondral allograft transplantation [25]. Disadvantages of this method compared to autografting are low risks of immune reactions, possible disease transmission, and slower graft incorporation [26,27]. A review article described that the graft failure rate ranges from 4 to 21% at 35–48-month follow-up and 15–39% at 7.5–21.8-year follow-up [28].

2.4. Autologous chondrocyte implantation (ACI) and matrix-assisted chondrocyte implantation (MACI)

Autologous chondrocyte implantation was first introduced by Peterson in the mid-1990s [29]. It is based on the concept of using cultured chondrocytes harvested from the articular cartilage, which are responsible for the development and repair of the extra-cellular matrix. There are two stages involved in this procedure (Figs. 3 and 4). In the first stage, chondrocytes are harvested from a non-weight-bearing surface, usually from the superior or the lateral aspect of the intercondylar notch or trochlea, and cultured [30,31]. In the second stage surgery, a periosteal membrane or porcine collagen material is sutured over the cartilage defect and the cultured chondrocytes are injected under the periosteal or porcine patch. The implanted cells proliferate and generate extracellular matrix to fill the cartilage defect with hyaline-like articular cartilage [29,32]. Several studies have shown good functional improvement and symptom relief after ACI [33–35]. A study showed 81% of patients had significant functional improvement and symptom relief at 3-year follow-up [33]. Another study showed that of a total of 100 patients who underwent ACI and were successfully followed up (with a mean follow-up time of 10.4 years), 98 were satisfied with the postsurgical results [35]. As for donor site morbidity, McCarthy et al. showed no significant donor site morbidity after chondral harvest for ACI treatment [31].

Matrix-assisted chondrocyte implantation (MACI) uses a porcine collagen membrane with seeded autologous cultured chondrocytes. This procedure also involves two steps. The similar first step is harvesting and culturing the chondrocytes from a non-weight-bearing surface, and then seeding the chondrocytes on the collagen matrix. In the second step, the collagen matrix with the seeded chondrocytes is implanted into the osteochondral defect with fibrin glue [36]. A systemic review article demonstrated good clinical outcomes and significant clinical improvement in patients who underwent MACI at long-term follow up [37]. This was qualitatively assessed by improved Knee injury and Osteoarthritis Outcome Scores (KOOS). Salzmann et al. [38] is a comparative study, which showed better clinical improvement in patients treated with MACI than with ACI. Nawaz et al. described the overall graft survival rate for both ACI and MACI is 78% at 5 years and 51% over 10 years [34].

2.5. Biomaterial processed allograft

There are new cartilage repair techniques using processed allograft material in conjunction with marrow stimulation to produce improved articular cartilage repair tissue. These industry-produced off the shelf biologic treatments offer potential point of service care that can be sized to the cartilage defect, akin to a pothole filling approach. Some use a tissue engineering approach to create biodegradable scaffolds seeded with chondrogenic cells and key components of the extracellular matrix such as type II collagen, proteoglycans, and cartilaginous growth factors.

Cartiform® (Osiris Therapeutics, Inc., Columbia, MD, USA) is a cryopreserved viable osteochondral cartilage allograft mesh. It is a round disc fenestrated with small pores, which provide tissue flexibility and conformation to contours of chondral surfaces. The mesh is comprised of viable chondrocytes, extracellular matrix, and chondrogenic proteins. The hypothesized mechanism of action is that the disc induces mesenchymal stem cells to undergo migration and chondrogenesis within the pores of Cartiform and production of type II hyaline-like repair cartilage [39]. There are several advantages compared to other surgical methods. Cartiform® produces improved articular cartilage repair tissue with type II collagen compared to marrow stimulation alone, demonstrated in an in vivo goat study [39]. There is one clinical report showing improvement of the patient's symptoms and mobility after the surgery. The postoperative biopsy contained predominantly type II hyaline cartilage at the osteochondral repair site [40].
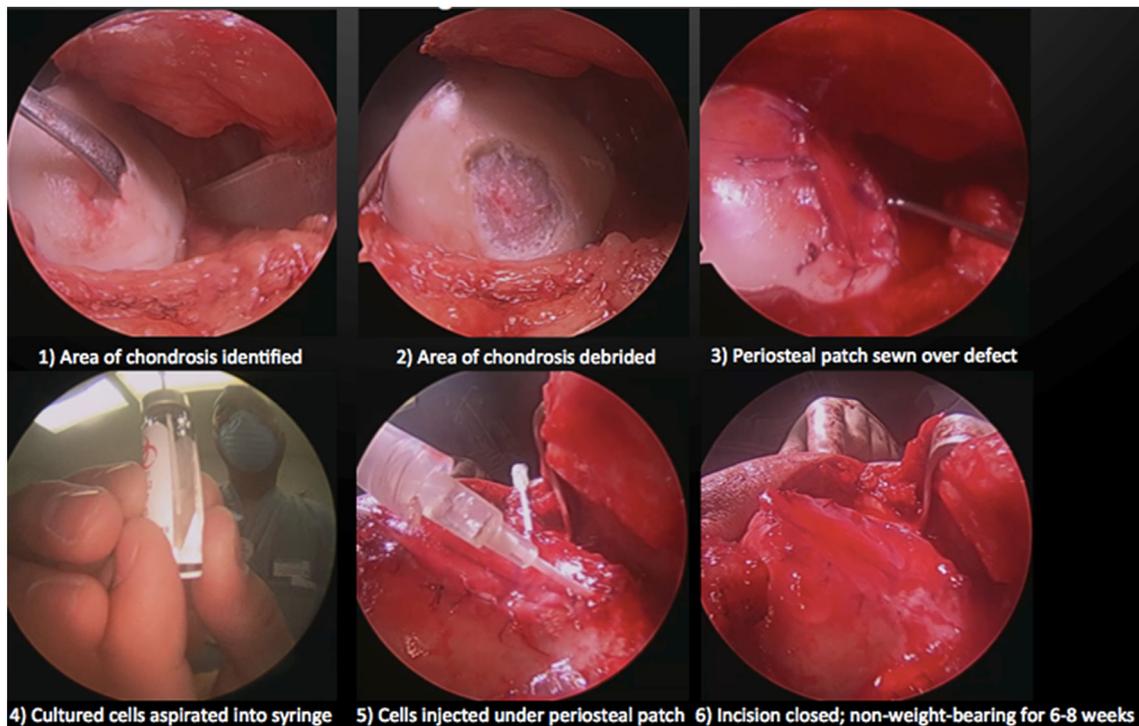
Fig. 4. Intraoperative images of autologous chondrocyte implantation (ACI) describe each step of the second stage of this procedure.

Cartiform® has a long two-year shelf life compared to the short shelf life of fresh osteochondral allograft, which is approximately 30 days. Additionally, this allows a single step point of care procedure. This procedure can include microfracture followed by implantation of Cartiform®. Long-term clinical studies are lacking.

BioCartilage® (Arthrex, Inc., Naples, FL, USA) is an extracellular matrix used in conjunction with microfracture procedure to provide a more durable hyaline-like cartilage than reparative fibrocartilage produced by microfracture alone. BioCartilage® is developed from allograft cartilage and contains micronized extracellular matrix that is native to articular cartilage and additional growth factors. It functions as a scaffold over a microfracture site and provides a tissue network that can potentially signal autologous cellular interactions and stimulate adult stem cells to produce hyaline-like cartilage within the defect [41]. Currently, there are few clinical studies to evaluate for its surgical outcomes. One study showed improved cartilage repair with Bio-Cartilage® compared to that with microfracture alone in an equine model [42]. Clanton et al. showed excellent clinical results in 7 patients with mean follow-up interval of 8.4 months with no significant complication of the BioCartilage® itself [43]. As with Cartiform®, it is a single step point of care procedure to improve repair of an osteochondral defect.

Several other processed allograft products have also been recently introduced. ProChondrix® CR (AlloSource, Centennial, CO, USA) is a laser-etched, cryopreserved fresh osteochondral allograft. CarGel® (Smith & Nephew, London, UK) is liquid bioscaffold prepared by mixing a buffer, a chitosan solution, and the patient's whole blood. DeNovo® NT (Zimmer, Warsaw, IN, USA) is a scaffold-free natural tissue graft of juvenile cartilaginous allograft tissue. There is less published research on these processed allograft products as compared to Cartiform® and BioCartilage®.

2.6. Limitations

Most of the support for these various cartilage repair techniques is based on anecdotal evidence and small studies. Cochrane reviews of cartilage repair surgeries of the knee have found insufficient evidence

to draw conclusions regarding the best surgical option for treating isolated cartilage defects and emphasized the need for further good quality randomized controlled trials for evaluating long-term functional outcomes [44,45]. However, a more recent study did show that patients with cartilage repair surgery (OATS or MACI) showed less progression of degenerative MRI changes at 6-year follow-up compared to a control cohort [46].

3. MR imaging techniques

MR imaging has become the most important method to visualize the articular cartilage of the knee and evaluate for chondrosis. It is non-invasive (or less invasive than arthroscopy if an arthrogram is performed) and provides a more comprehensive assessment of repair tissue, including the articular surface and bone-cartilage interface. MR imaging provides assessment of cartilage healing and can identify potential postsurgical complications. Repair cartilage can be evaluated with conventional MR sequences used in the assessment of native cartilage.

MR imaging techniques for anatomic and morphologic evaluation of cartilage include conventional spin-echo (SE), gradient recalled echo (GRE), and fast SE sequences (Table 1) [47,48]. Intermediate weighted fast spin echo sequences are the mainstay for evaluation of the articular cartilage with conventional MR imaging. There are also new 3D MR imaging techniques with isotropic voxels that allow multi-planar reformatting and reduce volume averaging artifacts (Table 2).

MR imaging can also evaluate the collagen network and proteoglycan content of the cartilage matrix with compositional MR techniques, which includes T2 mapping (Fig. 5), T1ρ imaging, delayed gadolinium-enhanced MR imaging of cartilage (dGEMRIC), sodium (Na-23) MR imaging, and diffusion-weighted imaging (DWI) (Table 3) [47,48]. Each MR imaging technique has its strengths and weaknesses for various applications.

4. MR imaging features of cartilage repair

Postoperative evaluation of articular cartilage repair usually

Table 1
Summary of conventional anatomic MR imaging techniques.

Technique	Strengths/suggested applications	Weaknesses
T1-weighted	• Anatomic detail • Fat, hemorrhage • Bone marrow evaluation, particularly differentiating red marrow from other pathology	• Poor contrast between cartilage and fluid • Poor detection of soft tissue edema • Not as sensitive as STIR or T2 with fat saturation for marrow edema
T2-weighted ± fat saturation	• Good contrast between cartilage and fluid • At 3 T, T2-weighting with fat saturation is good for evaluation of cartilage and better than PD for evaluation of marrow pathology	• Frequency-selective fat-suppression may be incomplete due to local field inhomogeneities • Bone marrow edema detection poor without fat saturation
Proton density (PD) ± fat saturation	• Good contrast between articular cartilage and joint fluid • Good for evaluation of internal cartilage signal	• Poor detection of fluid and marrow pathology without fat saturation • Susceptible to magic angle effects • Frequency-selective fat-suppression may be incomplete due to local field inhomogeneities
Short tau inversion recovery (STIR)	• Good for marrow and soft tissue pathology • Produces uniform fat saturation with less susceptibility to magnetic field inhomogeneities	• Poor signal-to-noise ratio (SNR) and contrast-to-noise (CNR) ratio • Poor evaluation of cartilage
Gradient (recalled) echo (GE or GRE)	• High spatial resolution • Fibrocartilage (meniscus, labrum) • Detection of loose bodies and hemorrhage	• Poor detection of marrow pathology • Metallic hardware artifacts due to susceptibility

includes the degree of osteochondral defect filling (thickness), graft signal intensity (overall heterogeneity), integration of the peripheral cartilage and bone interfaces, changes in the subchondral bone (e.g. edema and cysts), and presence of synovitis. The appearance of MR imaging varies with different repair techniques. Some of these changes may be considered normal in the early postoperative period but may be signs of treatment failure if they persist.
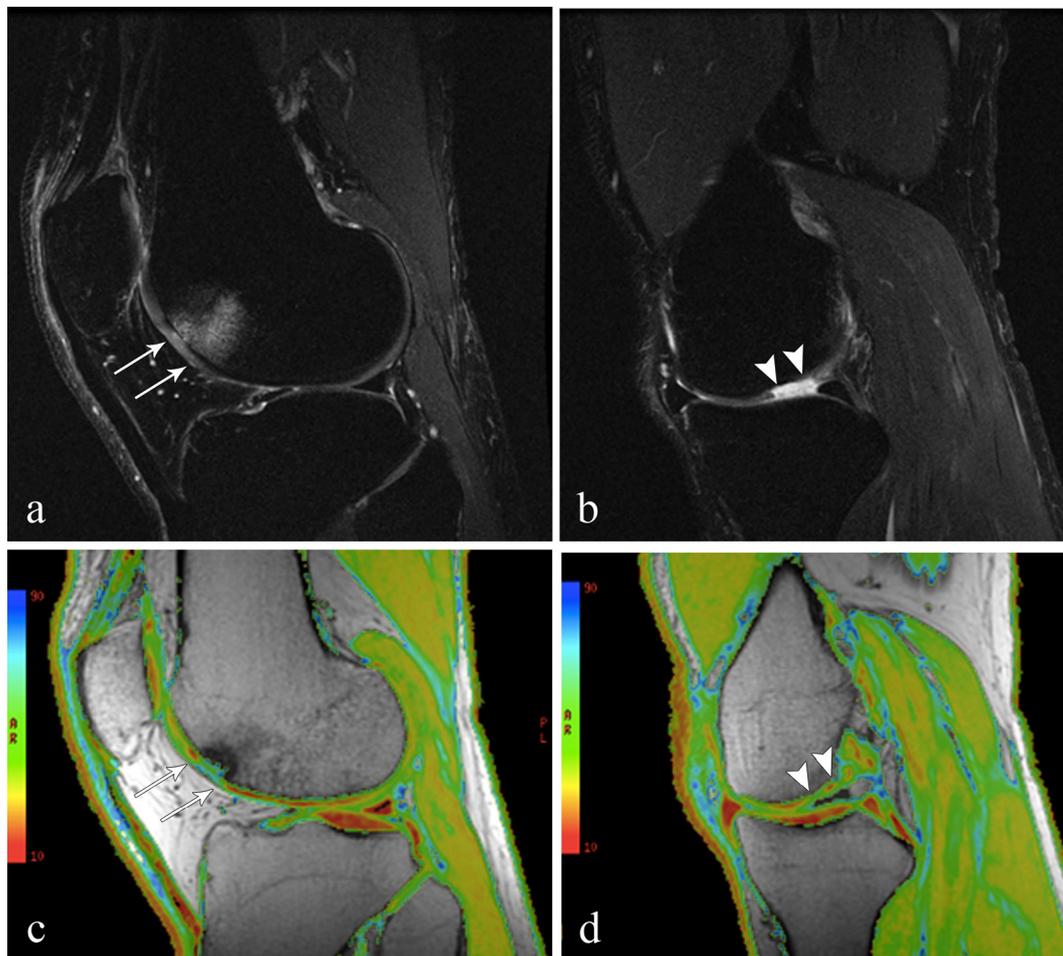
4.1. Bone marrow stimulation (microfracture)

During the early postoperative period (within first six months), the repair tissue is poorly organized with high water permeability and appears hyperintense to native cartilage on fluid-sensitive images; therefore, the newly formed fibrocartilage may be difficult to distinguish from adjacent fluid and may appear thin [7]. The repair tissue should continue to fill in the cartilage defect over time and become smooth at the articular surface by 1 or 2 years after surgery (Fig. 6) [7,13]. The signal intensity of the reparative tissue gradually decreases as the fibrocartilage matures. The subchondral bone marrow edema also decreases over time [13,49]. Persistent bone marrow edema and incomplete filling of the cartilage defect with irregular reparative tissue after 2 years suggest failure of treatment [7,10,50].

4.2. Mosaicplasty or osteochondral autograft transfer system (OATS)

Postoperative evaluation of osteochondral autograft should include assessments of the degree of osteochondral defect filling, graft signal intensity, integration of the peripheral cartilage and bone interfaces, contour of the articular surface, and changes in the subchondral bone. The transplanted autograft should completely fill the defect with homogeneous cartilage, without gaps between the graft and adjacent cartilage or bone (Fig. 7). Bone marrow edema in the autograft and adjacent bone can be seen in approximately 50% of patients during the first year, and up to 3 years in approximately 15% of cases after the procedure [7,13]. Bone marrow edema gradually resolves as the bone incorporation progresses. Persistent bone marrow edema and subchondral cyst formation signify poor tissue integration [5,7,51]. Depression of the plug < 1 mm can still have good clinical outcomes, but proud grafts can increase contact pressure and lead to degenerative changes [52,53]. Fissuring between the graft and native cartilage is also a sign of early graft failure [20]. Osteonecrosis is a rare complication [51]. The donor site should also be evaluated. The defect at the donor site is expected to gradually fill with fibrocartilage and bone. Persistent bone marrow edema at the donor site may indicate donor-site morbidity, which occurs in 5.9% of cases and may present as pain, knee

Table 2
Summary of 3D anatomic MR imaging techniques.

Technique	Strengths/suggested applications	Weaknesses
3D FSE (fast spin echo)	• 3D sequences can produce higher spatial resolution • Thinner sections compared with 2D FSE, decreasing partial volume averaging effects • Isotropic voxels allow multiplanar reformatting and decrease in partial volume artifacts	• Lower tissue contrast • Potential for blurring due to use of longer echo trains and parallel imaging compared with 2D sequences • Suboptimal assessment of subchondral bone
3D SPGR (spoiled gradient recalled echo)	• Standard technique for 3D morphologic imaging • Higher sensitivity than routine 2D FSE • Useful for quantification of cartilage thickness and volume • Isotropic voxels allow multiplanar reformatting and decrease in partial volume artifacts	• Long acquisition times • Lack of reliable contrast between fluid and cartilage • Metallic hardware artifacts due to susceptibility
3D DESS (double-echo steady-state)	• Faster acquisition times than SPGR • High SNR and cartilage-to-fluid contrast • Isotropic voxels allow multiplanar reformatting and decrease in partial volume artifacts	• Intrasubstance signal intensity changes in cartilage may be difficult to detect • Poor assessment of marrow pathology • Metallic hardware artifacts due to susceptibility
3D balanced SSFP (steady-state free precession)	• High signal-to-noise ratio (SNR) and cartilage-to-fluid contrast • Useful for assessing ligaments and menisci • Isotropic voxels allow multiplanar reformatting and decrease in partial volume artifacts	• Long time to repetition (TR) leads to banding artifacts at long repetition times, especially at higher field strength • VIPR (Vastly Undersampled Isotropic Projection Imaging), combines balanced SSFP imaging with 3D radial k-space acquisition to reduce banding artifacts

Fig. 5. 62-year-old male with left knee pain. Sagittal T2-weighted fat saturation (FS) MR images (a, b) demonstrate full-thickness chondral defect involving the lateral trochlea with subjacent marrow edema (*arrows*) and an additional near full-thickness chondral defect of the posterior weight-bearing surface of the medial femoral condyle (*arrowheads*). There is corresponding T2 prolongation at the margins of these defects on the T2 map (c, d).

instability, or osteoarthritis [7,54].

4.3. Osteochondral allograft transplantation surgery

MR imaging evaluation of the osteochondral allograft is similar to autograft, which includes degree of defect fill, graft signal intensity, interfaces between the cartilage and bone, congruity of articular surface, and any changes to the subchondral bone. The defect fill should provide a smooth articular contour (Fig. 8). Bone marrow edema in the graft and surrounding bone is usually seen during the first 3 months postoperatively, and gradually decreases thereafter [7,13]. Persistent bone marrow edema for > 1 year, gap between the graft and adjacent native bone, and articular surface collapse are signs of graft rejection or incomplete incorporation [7,13,27]. The step-off between the subchondral bone of the graft and adjacent host subchondral bone plate can be normal, as long as the cartilage surface is flush. This finding is due to a mismatch of the cartilage thickness between the donor and host sites and should not be confused for a subchondral spur. [55].

4.4. Autologous chondrocyte implantation (ACI) and matrix-assisted chondrocyte implantation (MACI)

Cartilage repair tissue hyperintensity relative to native cartilage (Fig. 9), incomplete filling, and subchondral bone marrow edema are often seen early after surgery. Osteochondral defect filling, decreased hyperintensity in repair tissue, and resolution of bone marrow edema typically occur during the first two years in over 90% of patients

[7,56,57]. The initial post-operative appearance depends on the type of chondrocyte implantation procedure that was performed. For autologous chondrocyte implantation, there is usually complete filling or slight overfilling. Underfilling may be present early after matrix-assisted chondrocyte transplantation with complete filling over 1–2 years [7]. Persistent incomplete filling and bone marrow edema may suggest treatment failure. Poor integration of the repair tissue to the underlying bone may occur at their interface, resulting in delamination. Delamination is identified by fluid signal intensity between the cartilaginous repair tissue and subchondral bone. Graft hypertrophy may be seen after autologous chondrocyte implantation as a complication in approximately 20–30% of cases, which may require surgical debridement and is associated with less favorable outcomes [58,59]. The newer generation of ACI uses synthetic collagen, which has a lower incidence of graft hypertrophy and delamination than the periosteal flap in classical ACI [5].

4.5. Biomaterial allograft

Carter et al. recently described the MR imaging findings in patients who underwent microfracture in conjunction with BioCartilage® graft [60]. The repair tissue should completely fill in the chondral defect and show complete integration with the subchondral bone and adjacent native cartilage (Fig. 10). The repair tissue may be inhomogeneous with lower signal intensity than the surrounding native cartilage. Incomplete fill, poor integration of the repair tissue, and persistent bone marrow edema and joint effusion usually indicate poor clinical outcomes.

Table 3
Summary of compositional MR imaging techniques.

Technique	Component assessed	Strengths/reported applications	Weaknesses
T2 mapping	• Collagen network, water content	• Well validated; compatible with most MR systems (1.5 T and higher) • Evaluation of cartilage repair tissue after microfracture, osteochondral grafting, and matrix-assisted autologous transplantation; evaluation of graft maturation after autologous chondrocyte implantation • Does not require contrast material administration	• Long acquisition times with multi-echo spin-echo sequence • Physical activity seems to play a role in cartilage T2 values
T2* mapping	• Collagen network, water content	• Faster acquisition than T2 mapping • Evaluation of cartilage repair tissue after microfracture • Does not require contrast material administration	• Not fully validated; susceptible to postoperative magnetic field inhomogeneities and magic angle artifact
T1 ρ (rho)	• Collagen network, glycosaminoglycans	• Sensitive to early cartilage degeneration • Evaluation of cartilage repair tissue after microfracture • Does not require contrast material administration	• Collagen fiber orientation and the concentration of other macromolecules may contribute to variations in T1ρ values • Cannot specify the macromolecular change in cartilage degeneration, it is "nonspecific" in the detection of early lesions • Requires special pulse sequences, typically available only at research institutions • Requires time-consuming multiple datasets
Delayed gadolinium enhanced MRI of cartilage (dGEMRIC)	• Glycosaminoglycans	• Well validated • Measurements correlate indirectly with glycosaminoglycan content	• Requires use of intravenous contrast material with time delay before acquisition • The dGEMRIC index has been shown to be affected by a number of physiologic factors, including exercise and body mass index
Sodium (Na-23) MR imaging	• Glycosaminoglycans	• Correlates directly with GAG content • Does not require contrast material administration • Differentiation between normal articular cartilage and matrix-assisted autologous transplantation repair tissue	• Lower SNR compared to proton MR imaging • Special hardware is required, only available at a few sites • Long acquisition times
Diffusion weighted imaging (DWI)	• Collagen network, glycosaminoglycans	• Duration of the sequence is short • Differentiation between normal articular cartilage and microfracture and/or matrix-assisted autologous transplantation repair tissue • Does not require contrast material administration	• Semi-quantitative image processing is demanding • Susceptible to motion artifacts
Chemical exchange saturation transfer (CEST)	• Glycosaminoglycans	• Directly quantifies GAG content based on the chemical exchange of its labile hydroxyl (-OH) protons with the bulk water • Does not require contrast material administration	• Susceptible B_0 inhomogeneity requires accurate B_0 correction • Long scan times and low signal-to noise ratio
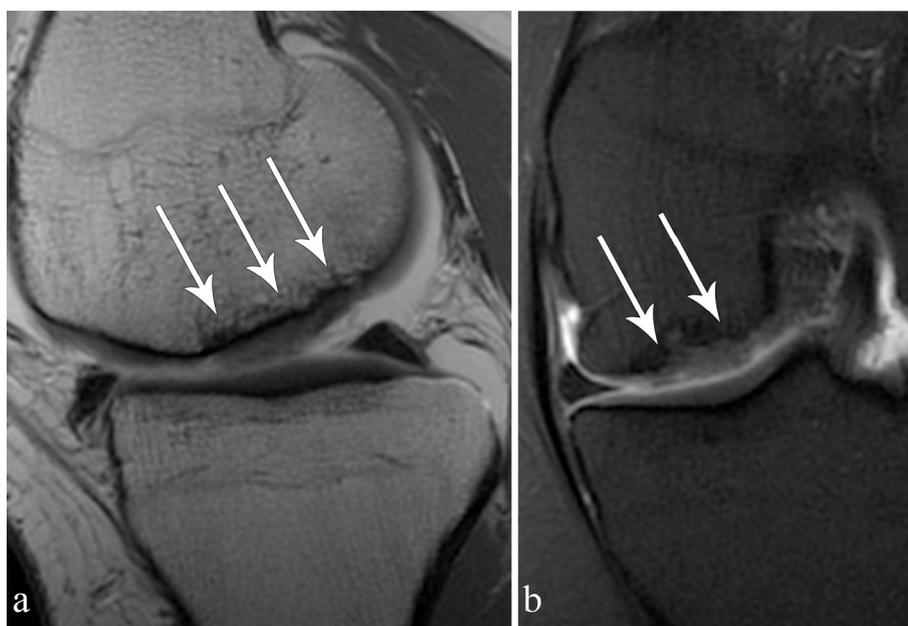
Fig. 6. Sagittal proton-density (PD) (a) and coronal T1 fat-saturated (FS) (b) MR arthrogram images demonstrate subchondral marrow changes related to the prior microfracture (*arrows*) with overlying fibrocartilage fill-in.
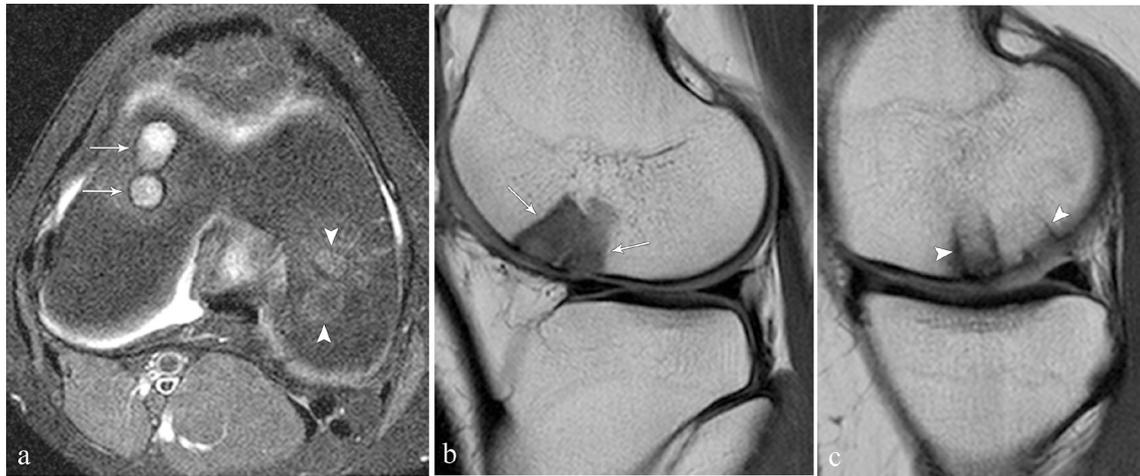
Fig. 7. 23-year-old female status post osteochondral autograft transfer system (OATS) procedure. Axial PD FS (a) and sagittal PD (b, c) MR images demonstrate transfer of osteoarticular bone plugs from the non-weight-bearing lateral femoral trochlea (*arrows*) to the weight-bearing surface of the medial femoral condyle (*arrowheads*).

Interestingly, Carter et al. found that positive clinical outcomes did not correlate significantly with the degree of defect fill, presence of an intact surface, intact subchondral bone, or lack of effusion [60]. The features associated with good clinical outcomes were presence of adhesions and intact subchondral lamina [60]. However, the sample size was small and only 6 case studies were included in the study. Further investigation with larger patient populations is needed to elucidate the clinical correlations.

5. Morphologic scoring systems

Several MRI scoring systems have been described to assess the imaging characteristics after cartilage repair in the literature. MOCART (MR Observation of Cartilage Repair Tissue) is a reproducible, semi-quantitative scoring system for the assessment of morphologic cartilage repair and is the most commonly utilized system. MOCART uses 9 structural variables to assess the imaging features (Table 4) [61]. It was originally developed to evaluate ACI repair. MOCART is useful in clinical follow-up of cartilage repair and may be used to compare the outcomes of different surgical repair techniques in longitudinal clinical studies. In particular, defect fill and changes in the subchondral bone have good correlation with clinical outcome [62]. Another commonly used scoring system is the Henderson classification system, based on the degree of defect filling (1 = complete, 2 > 50%, 3 < 50%, 4 = none), cartilage signal intensity (1 = normal, 2 = slight hyperintensity, 3 = larger areas of hyperintensity, and 4 = absent), and subchondral edema and joint effusion (both graded as 1 = absent, 2 = mild,

3 = moderate, and 4 – severe) [57].

A meta-analysis study analyzed various MRI classification systems and features to assess their correlation with clinical outcomes after cartilage repair surgeries of the knee [63]. Although the MR imaging correlates with postsurgical outcomes, MR imaging correlations vary with the type of surgery. The outcome of microfracture correlates most significantly with the Henderson score, subchondral edema, and repair tissue signal. The outcome of ACI correlates most strongly with the Henderson score, repair tissue signal, and graft hypertrophy. The outcome of OATS correlates most significantly with osteochondral defect fill and repair tissue structure [63]. Many MRI findings (hyperintense signal of repair tissue, subchondral edema, effusion, etc.) may be part of the normal repair process; therefore, the MRI classification systems have limited utility in the early postoperative period.

6. Conclusion

This article reviews the various types of cartilage repair surgeries for the knee, including bone marrow stimulation (microfracture), osteochondral autograft transfer system (OATS) or osteochondral allograft transplantation, autologous chondrocyte implantation (ACI), matrix-assisted chondrocyte implantation (MACI), and other newer processed allograft cartilage techniques. As these surgeries become more widely adopted and increase in prevalence, it is important to recognize the normal imaging appearances of these various cartilage repair surgeries and the MRI findings of potential postsurgical complications.

Fig. 8. 48-year-old male with osteochondral allograft placement. Axial T2-weighted (a), sagittal T1-weighted (b) and coronal PD FS (c) MR images demonstrate osteochondral allograft at the weight-bearing surface of the medial femoral condyle (*arrowheads*), fixed with bioabsorbable pins.
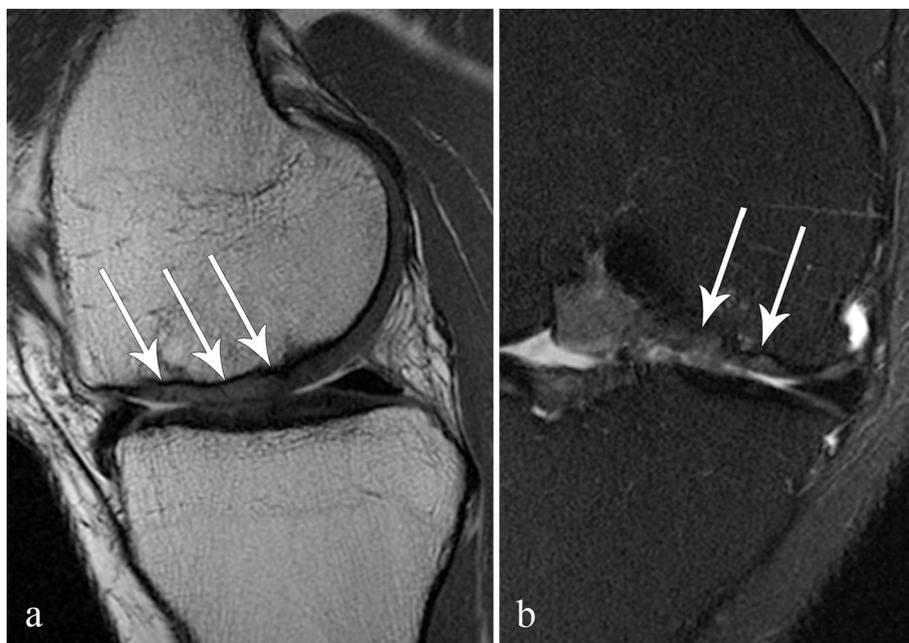
Fig. 9. 37-year-old woman with prior autologous chondrocyte implantation (ACI) of the weight-bearing surface of the medial femoral condyle. Sagittal PD (a) and coronal PD FS (b) MR images demonstrate mild signal alteration but normal thickness of the implant (*arrows*).

Fig. 10. 16-year-old male with right knee pain. Axial (a) and sagittal (b) PD FS MR images demonstrate an osteochondral defect of the lateral femoral trochlea (arrows). Microfracture surgery with BioCartilage graft was performed 5 months later. Axial PD FS (c) and sagittal T2-weighted FS (d) MR images acquired 4 months after surgery demonstrate previous lateral femoral trochlear defect occupied by intermediate signal intensity cartilage graft which appears well incorporated (*arrowheads*).

Table 4
MOCART (magnetic resonance observation of cartilage repair tissue) scoring system.

Scoring category	Variable and MR imaging characteristic
Degree of defect repair and defect filling	• Complete → on a level with adjacent cartilage • Hypertrophy → over the level of the adjacent cartilage • Incomplete → under the level of the adjacent cartilage; underfilling
Integration to border zone	• Complete → complete integration with adjacent cartilage • Incomplete → incomplete integration with adjacent cartilage
Surface of the repair tissue	• Surface intact → lamina splendens intact • Surface damaged → fibrillations, fissures and ulcerations
Structure of the repair tissue	• Homogenous • Inhomogeneous or cleft formation

Signal intensity of the repair tissue	• T2-weighted fast spin echo (FSE)
	   • Isointense
	   • Moderately hyperintense
	   • Markedly hyperintense
	 • 3D gradient echo with fat suppression (3D-GE-FS)
	   • Isointense
	   • Moderately hypointense
	   • Markedly hypointense

Subchondral lamina	• Intact • Not intact
Subchondral bone	• Intact • Non-intact (edema, granulation tissue, cysts, sclerosis)
Adhesions	• No • Yes
Effusion	• No • Yes

Compliance with ethical standards

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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