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Basic Science and Surgical Treatment Options for Articular Cartilage Injuries of the Knee

Articular cartilage–related injuries have been recognized as a cause of significant morbidity since the time of Hippocrates in ancient Greece and affect approximately 1 million patients each year within the United States.[13,63] Such injuries can be limited to the superficial layers of cartilage or extend deep into the subchondral bone. Partial-thickness defects residing in the superficial layer are not always associated with clinical symptoms, whereas full-thickness defects extending to the subchondral bone often present with recurrent effusions, activity-related pain, and morbidity. Such defects are presumed to be the first step toward the progression of osteoarthritis.

The poor regenerative capacity of articular cartilage has led to innovative approaches to treating symptomatic lesions and alleviating patient symptoms. One of the earliest techniques, popularized by Pridie[51] in the 1950s, included drilling into subchondral bone to stimulate the release of marrow elements that could potentially heal a cartilage defect. This technique, although modified and now commonly performed as a microfracture, shows the best outcomes for competitive athletes under 40 years of age with femoral condyle lesions smaller than 2 cm^2 and moderate symptoms of less than 1 year in duration.[44] Additional techniques have been developed to specifically address larger lesions and defects in an active patient population. Whether patients undergo palliative, reparative, or restorative surgical techniques, the goals of each procedure are to reduce symptoms, return patients to their normal activity level, and allow for future treatment options should they be required. The purpose of this article is to review existing surgical options for chondral knee injury and to provide a current treatment algorithm established and applied at our institution.

SYNOPSIS: The complex structure of articular cartilage allows for diverse knee function throughout range of motion and weight bearing. However, disruption to the structural integrity of the articular surface can cause significant morbidity. Due to an inherently poor regenerative capacity, articular cartilage defects present a treatment challenge for physicians and therapists. For many patients, a trial of nonsurgical treatment options is paramount prior to surgical intervention. In instances of failed conservative treatment, patients can undergo an array of palliative, restorative, or reparative surgical procedures to treat these lesions. Palliative methods include debridement and lavage, while restorative techniques include marrow stimulation. For larger lesions involving subchondral bone, reparative procedures such as osteochondral grafting or autologous chondrocyte implantation are considered. Clinical success not only depends on the surgical techniques but also requires strict adherence to rehabilitation guidelines. The purpose of this article is to review the basic science of articular cartilage and to provide an overview of the procedures currently performed at our institution for patients presenting with symptomatic cartilage lesions. *J Orthop Sports Phys Ther 2012;42(3):243-253. doi:10.2519/jospt.2012.3673*

KEY WORDS: *chondral lesion, chondrocyte implantation, osteochondral grafts, surgical methods*

BASIC SCIENCE

Articular cartilage is an avascular and aneural tissue composed of chondrocytes and an extracellular matrix consisting of water, collagen,

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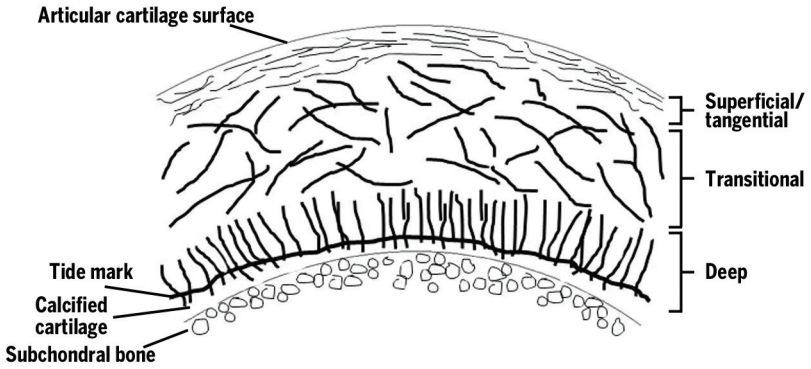

FIGURE 1. Schematic of hyaline cartilage layers.

and proteoglycans.[49] Due to its avascular nature, articular cartilage has low metabolic activity and poor regenerative capacity.[49] The cartilage of the knee is hyaline in nature, with an average depth of 2 to 4 mm, depending on location. Hyaline cartilage is composed of 2 separate phases (solid and fluid), each with specialized characteristics that allow for dynamic fluid shifts and compressibility during weight bearing. The solid phase contains collagen and proteoglycans, while the fluid phase is composed of water and ions.

The solid phase has high frictional resistance to fluid flow, thus low permeability, which causes a high interstitial fluid pressurization in the fluid phase.[49] The pressurization of this phase contributes more than 90% of load transmission of cartilage.[49] In the solid matrix, collagen molecules line up to form fibrils, with gaps giving rise to intramolecular and intermolecular crosslinking to stabilize the matrix.[49] Type II collagen is the primary component of hyaline cartilage and essentially encases proteoglycans, including aggrecan.[9] Aggrecan consists of negatively charged chondroitin and keratin sulfates that interact to form larger molecules of aggrecan found throughout the collagen matrix. These negatively charged sulfate groups interact with cations to form ion-dipole interactions with water, resulting in a well-hydrated tissue that resists compression.[9]

Water is the most abundant component of articular cartilage, comprising 65% to 80% of the wet weight. The majority of water in articular cartilage is located in the interstitial intrafibrillar space and is held in place by negatively charged proteoglycans.[49] This fluid phase provides the matrix with its time dependence, reversible deformability, and ability to dissipate load. Hydraulic pressure protects and shields stress burden from the solid phase.[49] The interaction between these phases is instrumental in giving articular cartilage its viscoelastic properties.

Chondrocytes account for 5% of the wet weight of articular cartilage and are responsible for the upkeep and maintenance of the extracellular matrix and cartilage.[3,49] Articular cartilage is histologically organized into 4 distinct zones (superficial, transitional, deep, and calcified layers), each with unique properties and characteristics[10] (**FIGURE 1**).

The superficial (tangential) zone makes up 10% to 20% of the articular cartilage thickness[49] and consists of a fibrillar sheet known as the lamina splendens, where densely packed collagen fibrils are arranged parallel to the surface with a flattened layer of chondrocytes. This zone resists shear stress, secretes lubricating proteins, has low fluid permeability, and deforms approximately 25 times more than the middle zone.[49] Clinically, this is often the first layer to break down and be visualized arthroscopically.

The transitional zone provides an anatomic and functional bridge between the superficial and deep zones, and is composed almost entirely of large-diameter, loosely packed collagen and obliquely shaped chondrocytes. There is less organization to the arrangement of collagen fibers, giving it a higher compressive modulus than the superficial zone.[49]

The deep layer is composed entirely of thick collagen fibers arranged perpendicular to the surface, and running parallel to them are columnar-shaped chondrocytes.[49] This layer has the highest compressive modulus, as it contains the lowest water concentration and highest proteoglycan concentration.[49] This zone plays a primary role in load distribution and resistance to compression forces.

The calcified layer is separated from the deep radial layer by the tide mark, a transitional area between hyaline cartilage and subchondral bone. This layer contains small cells embedded in the cartilaginous matrix with apatitic salts. Pathologic delamination may occur in this region, which is either preserved (cell-based therapy) or intentionally violated (marrow stimulation techniques) during cartilage repair procedures.

Each layer contributes biomechanical characteristics and properties to the overall structure that are necessary to bear loads and function with minimal friction. Although major advances have been made in existing cartilage repair technologies, predictable restoration of the unique weight-bearing properties of articular cartilage continues to elude surgeons.[9,11]

CHONDRAL LESIONS: INTERNATIONAL CARTILAGE REPAIR SOCIETY (ICRS) GRADING

A grading scale measuring the severity of chondral lesions is necessary for accurate and consistent physician communication and research documentation. Multiple classification systems have been described in the

literature. The most commonly used classification system was developed by Outerbridge, who divided chondral lesions into 4 separate grades but did not characterize lesion depth.[8] Although other systems have taken a lesion's depth, appearance, size, and location into account, none have been universally accepted and used to evaluate focal cartilage lesions.[8] Our institution prefers to employ the widely accepted grading system established by the ICRS.[8] This system is based on 2 factors: the depth of the lesion and the extent to which subchondral bone is involved (**TABLE**).

TABLE International Cartilage Repair Society Classification

Lesion Grade	Classification
0	Normal
1	Nearly normal: superficial fissuring
	A. Soft indentation
	B. Superficial fissures and cracks
2	Abnormal: lesion extending down to less than 50% of the cartilage depth
3	Severely abnormal: cartilage defect
	A. Extending down to more than 50% of the cartilage depth
	B. Down to the calcified layer
	C. Down to but not through subchondral bone
	D. Presence of blisters
4	Severely abnormal: penetrating subchondral bone
	A. Penetrating subchondral bone but not full diameter
	B. Penetrating subchondral bone and full diameter

EPIDEMIOLOGY

The incidence and prevalence of chondral defects within the knee joint are difficult to ascertain. Many lesions may be silent in nature, and growing evidence supports the concept that these asymptomatic lesions can develop and progress from partial- to full-thickness defects. Several retrospective studies have estimated the prevalence of this pathology. Curl et al[15] reviewed 31 516 knee arthroscopies and found that 63% of these patients had chondral lesions. In a more recent study, Widuchowski et al[63] reported similar results after reviewing 25 124 knee arthroscopies, and found that 60% of these patients were diagnosed with cartilage lesions and 58% revealed that the onset of symptoms was noncontact trauma (daily activities or skiing). Multiple studies have reported a high prevalence of grade III chondral lesions in the knee.[15,30] The most common location of reported cartilage lesions is the medial femoral condyle, followed by the lateral tibia and patella. The average chondral lesion surface area is 2.1 cm^2, and 88% of defects have less than 4 cm^2 of surface area.[30] The mean number of defects per knee is 2.7 lesions, and these defects are associated with a meniscal lesion in 42% of cases.[15] In addition, the majority of patients with chondral lesions are male and average 43 years of age.[15]

COMORBIDITIES

Other pathologies, such as meniscal injury or deficiency, malalignment, and ligamentous instability, are frequently encountered by the operating surgeon treating articular cartilage defects. These pathologies are known to contribute to the development of articular lesions. Corrective surgical intervention is crucial for effective and durable cartilage repair. Studies have reported that surgically addressing these combined pathologies ensures the integrity of the primary cartilage repair without affecting the patient's ability to return to daily activities. It is also advantageous to address combined pathologies at the time of the primary cartilage repair to avoid prolonged rehabilitation. The decision to proceed with concomitant versus staged procedures includes several factors. Staging requires multiple interventions and several recuperative periods. There is some research favoring the concomitant technique. Willey et al[64] found twice as many complications in a group of 35 patients (78 procedures) who underwent a staged osteotomy compared to an osteotomy combined with autologous cartilage implantation, osteochondral allograft transplantation, or other procedures. Conversely, concurrent reconstruction demands less recuperative time but increases surgical time and the risk of complications. In the opinion of the senior author (B.J.C.), a patient's compliance, the surgeon's expertise, and the clinical presentation should always be considered when deciding on the most appropriate approach for a patient.[24]

CONCOMITANT PATHOLOGY

Malalignment and meniscal deficiency lead to increased focal contact pressures in the knee and are the 2 most common concomitant pathologies that require treatment at the time of articular cartilage repair.[20] Partial and complete meniscectomies increase the contact stresses in the affected joint, resulting in approximately 6.5% volumetric loss of cartilage per year, and have been recognized as contributing factors to osteoarthritic changes in the knee.[12,35] Mills et al[43] found that cartilage defects were of greater severity in patients who underwent an arthroscopic partial medial meniscectomy compared to a control group of patients of similar age. Early repair of the anterior cruciate ligament allows the preservation of cartilaginous and meniscal stock, as elapsed time from ligamentous injury to repair is a prognostic factor in meniscal and osteochondral

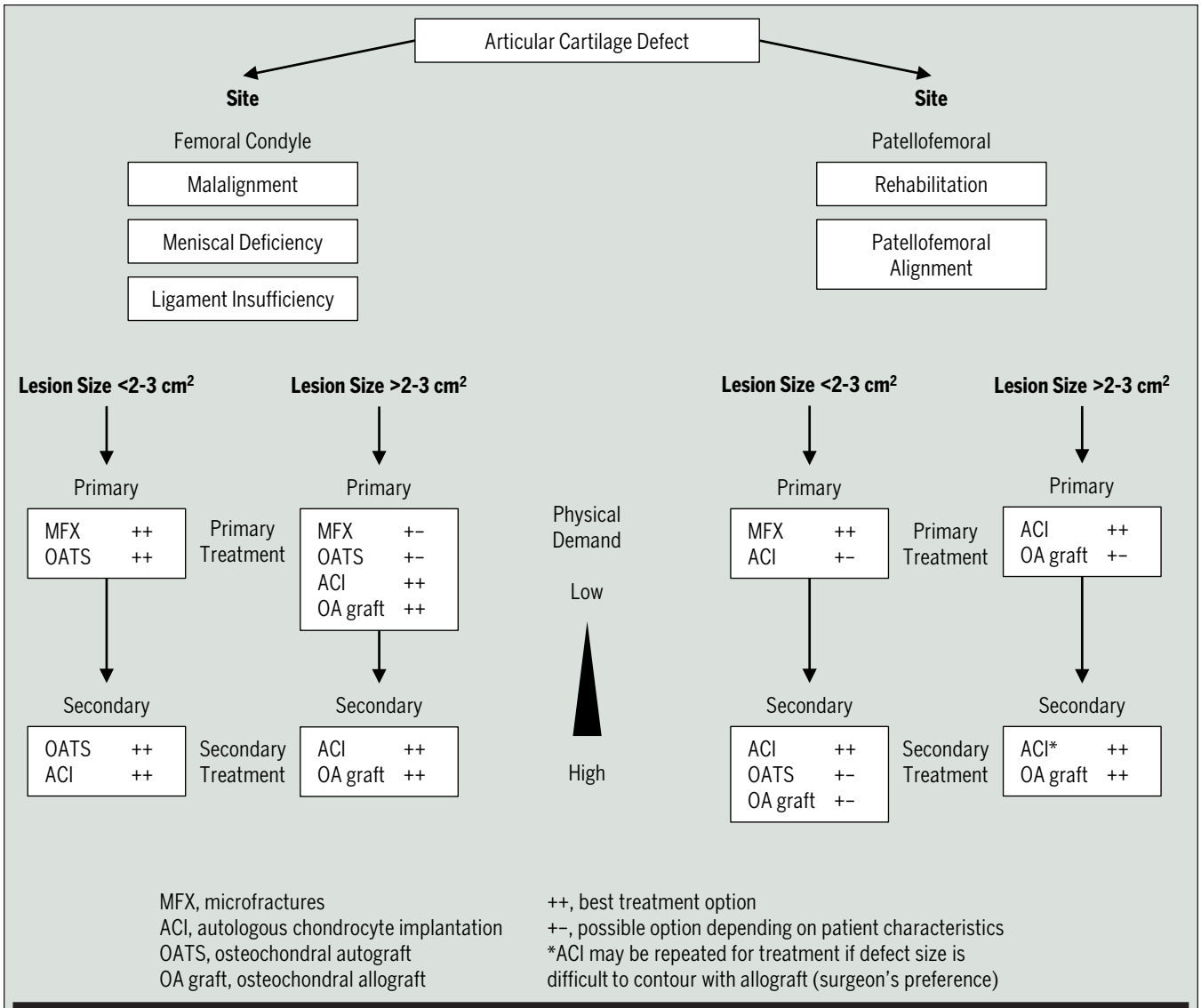

FIGURE 2. Treatment algorithm for reparative and restorative procedures for articular cartilage defects of the femoral condyle and patellofemoral sites, according to lesion size and physical activity level. It is critical to address knee joint comorbidities prior to treatment of a symptomatic chondral defect. Primary treatments should generally be attempted before secondary treatment lines are considered.

damage.[25] Over time, posterior cruciate ligament insufficiency significantly increases cartilage degeneration in the medial tibiofemoral and patellofemoral compartments.[60] Even after a successful ligament stabilization procedure, an associated, untreated cartilage lesion can still progress to a symptomatic defect.[18,37] Shirazi and Shirazi-Adl[54] found that a partial meniscectomy with anterior cruciate ligament laxity increased contact pressures and subsequently increased the risk of joint degeneration.

RESPONSE TO INJURY

In the early stages of chondrocyte injury, damage to the cellular membrane results in an efflux of intracellular contents that causes a decrease in the metabolic capacity of the cell, disrupting proteoglycan production and concentration. Subsequently, these changes in cell functionality cause increased tissue hydration and fibrillar disorganization of collagen.[36,38,39,47] This allows easier transmission of impact loads to damaged cartilage, starting a vicious degenerative cycle that is thought to contribute to the progression of partial-thickness injuries to full-thickness defects.[46] Full-thickness injuries that penetrate subchondral bone allow the influx of pluripotent marrow elements, which have been shown to have increased potential for intrinsic repair.[23] These cells typically regenerate type I collagen, or fibrocartilaginous repair tissue, which is biomechanically inferior to native type II hyaline cartilage.[3,55] Although the fibrocartilage is in place, it

is suspected to be unable to operate in a high-stress environment with respect to load bearing, which may lead to further cartilage degeneration and progression to osteoarthritis.[21]

CARTILAGE RESTORATION TECHNIQUES AND CONSIDERATIONS

Operative strategies can be grouped into palliative, reparative, and restorative techniques. Each technique has specific criteria pertaining to previously provided treatments, surgeon expertise, patient age, chronicity, concomitant pathology, and lesion depth. Individuals with low physical demands and a lesion size less than 2 cm^2 may elect to have a palliative procedure (arthroscopic debridement and lavage) as a first-line treatment, while a young patient with high physical demand may be better suited for a reparative or a restorative strategy. The reparative approach consists of marrow stimulation techniques that result in the formation of fibrocartilage, while restorative methods aim to replace damaged cartilage and/or subchondral bone with fully intact hyaline or hyaline-like tissue, using osteochondral or chondrocyte transplantation. A simple review of our surgical decision-making process for articular cartilage lesions with ICRS grades 3 and higher takes into account the lesion size and location, as well as the patient activity level (**FIGURE 2**). As mentioned previously, concomitant treatment of limb malalignment, ligamentous instability, or meniscus deficiency is also critical to a successful outcome following treatment of a symptomatic chondral defect.

Palliative Technique: Arthroscopic Lavage and Debridement

The first-line palliative treatment method is arthroscopic debridement and lavage. Debridement includes the smoothing of fibrillated articular or meniscal surfaces, the shaving of movement-restricting osteophytes, and the removal of inflamed synovium. Lavage of the joint clears fragments of cartilage[19] and calcium phosphate crystals.[62] Harwin[28] and other groups[16,17,56] have found that lavage and debridement are beneficial for a select group of patients presenting with acute pain, specific localized mechanical symptoms of locking or catching, minimal malalignment, and no previous history of surgery,[48] as opposed to patients with global arthritic changes.[31] Jackson and Dieterichs[33] found that lavage and debridement provide significant relief in patients with osteoarthritis if the intervention is performed during the acute stage of degeneration. Two separate prospective trials of debridement in individuals with limited degenerative osteoarthritis of the femorotibial joint[42] and lavage in individuals with non–end-stage knee osteoarthritis[32] displayed significant improvements in knee pain when compared to nonoperatively treated groups.

Reparative Technique: Microfracture

The most studied reparative technique is microfracture, which is a controlled perforation of the subchondral bone plate to permit the efflux of pluripotent stem cells and growth factors into a chondral lesion.[58,59] These released elements stimulate the production of a fibrin superclot, which allows for the differentiation of cells to fibrochondrocytes. This reparative fibrocartilage contains a high concentration of type I collagen, which does not have the ability of type II hyaline cartilage to resist compression and shear load.[6]

In the experience of the senior author (B.J.C.), ideal indications for microfracture include contained, unipolar (isolated lesion in 1 compartment of the knee) ICRS grade 3 or 4 lesions of less than 2 cm^2 without bone loss in active patients. Cartilage is removed arthroscopically by eliminating the calcified layer, and well-defined, sharp vertical boundaries of normal cartilage are created to provide an optimal mechanical environment that reduces shear and compressive forces. Next, a surgical awl is used to create a bed of small perpendicular holes that are spaced 2 to 3 mm apart.[14,59] Proper drill depth is confirmed by decreasing the arthroscopic fluid influx and visually assessing the efflux of blood and marrow elements from the holes (**FIGURE 3**).

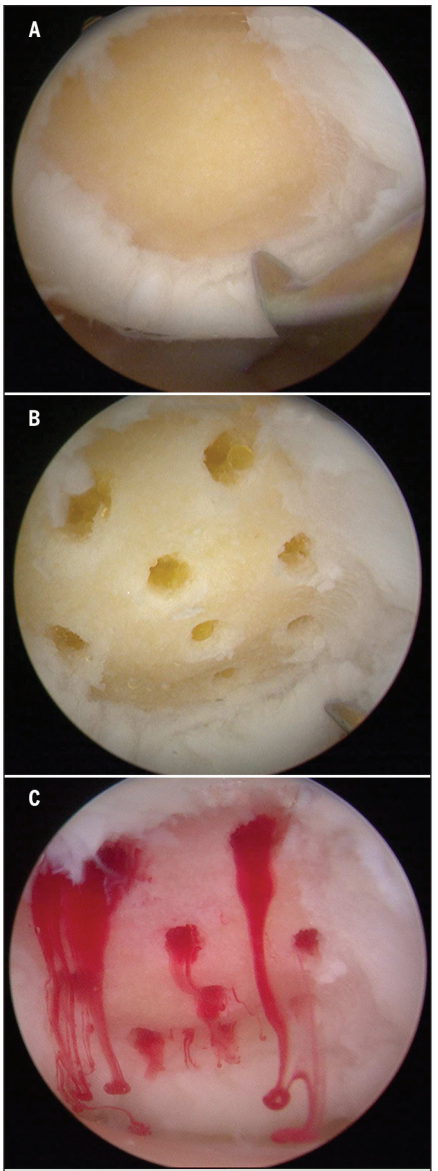

FIGURE 3. Arthroscopic microfracture of a medial femoral condyle (MFC) defect in a right knee. (A) Debrided MFC articular cartilage lesion with well-shouldered, healthy articular cartilage. (B) Completed perforation of subchondral bone. (C) Efflux of marrow elements into lesion site from subchondral bone.

The postoperative rehabilitation protocol depends on the location of the lesion but most commonly involves 6 to 8 weeks of touchdown weight bearing and

the use of a continuous passive motion (CPM) device for 6 to 8 hours per day, set at 1 cycle per minute. Use of CPM in patients following cartilage repair of the knee improves regenerate fibrocartilage and function.[52] For femoral condyle lesions, the range of motion begins at a level of flexion that is comfortable for the patient, advancing 10° daily until full flexion is reached. During this time, the patient must adhere to touchdown weight bearing (20%-30% of body weight). The patient gradually returns to full weight bearing after week 8 and should be at full weight bearing by week 12. For trochlear or patellar lesions, the patient is initially weight bearing as tolerated, with a range of motion from 0° to 40° of flexion with a knee brace and a CPM device. After 8 weeks, patients must progress to full weight bearing and full range of motion without pain, with full return to exercise by 12 weeks and discouragement of resisted knee extension until after 6 months. A combination of a well-executed procedure and compliance with postoperative rehabilitation guidelines may offer symptomatic relief while preserving the possibility of other treatment options in the future.

Steadman et al,[57] in the first published long-term study with a follow-up of 11 years in 72 patients (75 knees) who underwent a microfracture procedure, reported improvement in 80% of the patients using multiple clinical outcome measures. Similarly, Mithoefer et al[45] reported that 67% of 48 patients, at a mean follow-up time of 3.6 years, reported good to excellent functional improvements. The preceding authors found that an age of less than 35 years,[57] a body mass index[45] of less than 30 kg/m^2, a defect location of the femoral condyle,[14] and size[26] of less than 2 cm^2 coincided with more successful outcomes with microfracture.

Restorative Technique: Autologous Chondrocyte Implantation

Autologous chondrocyte implantation (ACI) is a restorative technique that results in the formation of hyaline-like cartilage and has been shown to provide relief for patients with large defects and high postoperative expectations. ACI is a 2-stage procedure that is indicated for young patients (15 to 50 years of age) with moderate symptoms and well-contained full-thickness femoral chondral lesions measuring between 2 and 10 cm^2 with an intact bone bed. In addition, a previous failed arthroscopic debridement and lavage, microfracture, or osteochondral autograft or allograft warrants consideration of an ACI as a restorative option.[7] Contraindications include bipolar lesions (2 kissing lesions located within the same compartment of the knee [femoral condyle and tibial plateau]), untreated malalignment, ligamentous instability, and T2-weighted magnetic resonance imaging evidence of defects that involve subchondral bone.

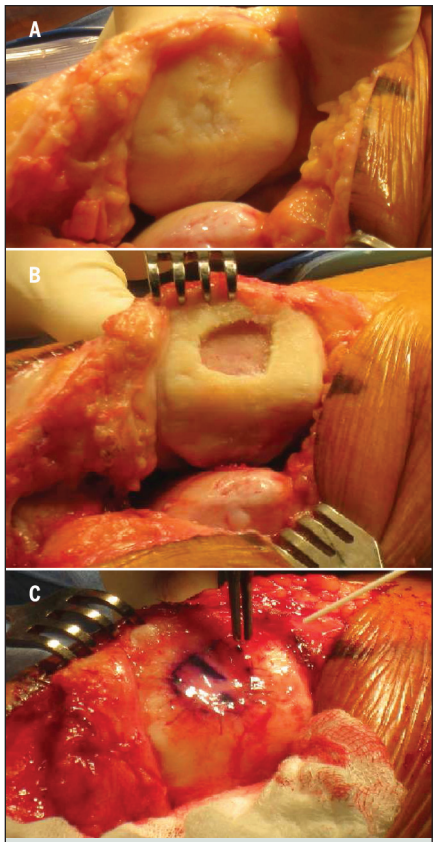

FIGURE 4. Autologous chondrocyte implantation. (A) Focal chondral defect on the articular surface of the patella. (B) Debridement of the patellar lesion to subchondral bone with stable vertical walls and abutting healthy articular cartilage. (C) Synthetic patch (off-label usage) sewn over prepared patellar lesion site and implantation of cultured chondrocytes through an angiocatheter.

The first stage of ACI surgery involves an arthroscopic evaluation of the lesion and biopsy of normal articular cartilage (200-300 mg) from a non–weight-bearing region (intercondylar notch or upper medial femoral condyle) for in vitro chondrocyte dedifferentiation and expansion. The second stage of the procedure normally occurs 6 weeks later and consists of an arthrotomy to expose the lesion site. The defect is carefully debrided of scar tissue and fibrocartilage, and a sharp curette is used to form vertical walls of normal cartilage.[41] The creation of stable vertical walls allows for easy placement of a synthetic patch over the lesion site (an off-label use of the Bio-Gide [Geistlich Biomaterials, Wolhusen, Switzerland], which has not been approved by the US Food and Drug Administration for cartilage repair, though many like it are on the market and used with indication for tendon reconstruction).[34] The patch is then carefully sewn into place and sealed using fibrin glue (**FIGURE 4**). A small opening toward the top of the patch is utilized to inject the cultured chondrocytes. Chondrocytes are delivered using an angiocatheter and, once implanted, the gap is sealed using suture and fibrin glue.

Overall, the rehabilitation protocol differs by lesion location. Specific range-of-motion and weight-bearing guidelines for a femoral condyle lesion require the use of CPM for 6 to 8 hours a day in 2-hour increments for the first 4 weeks, set at 1 cycle per minute, to assist in cellular orientation and adhesion prevention. Continuous passive range of motion is set from 0° to 30°, increasing 5° to 10° per day and reaching 90° by the fourth week and 120° by the sixth week. Patients wear a brace locked in extension for the first 2 weeks and opened in 20° increments as quadriceps control is gained, with the goal of removing the brace by week 12. In addition, non–weight bearing is observed for the first 2 weeks, with progression to

partial weight bearing (14-18 kg) over the following 2 weeks. The use of 1 crutch is then allowed until 6 weeks after surgery, at which point the patient progresses to full weight bearing. Return to normal activities of daily living and sports activities is allowed approximately 6 months after surgery.

Zaslav et al[67] prospectively followed 154 patients who were treated with an ACI procedure and reported that 77% of patients had good to excellent clinical outcomes based on knee function, knee pain, quality of life, and overall health. Similar prospective studies were completed by Rosenberger et al,[53] who reported that 72% of 56 patients subjectively reported a good to excellent outcome.

Restorative Technique: Osteochondral Autograft Transfer System

A larger defect that involves subchondral bone requires an osteochondral autograft or allograft transplantation. The osteochondral autograft transfer system procedure is indicated for symptomatic, unipolar lesions of the distal femoral condyle that are less than 2 cm^2 in a nondegenerative joint in patients with an upper age limit of 50 years. Proper limb alignment, ligamentous stability, and meniscal competence must be corrected to avoid premature wear of the transplanted cartilage.[27]

Osteochondral autograft transfer can be completed arthroscopically or via a small arthrotomy. Multiple studies have shown that donor site regions of the medial trochlea (which has the lowest contact pressure[22]), the lateral trochlea, and the intercondylar notch have minimal patellofemoral contact and thus are the preferred sites for donor plug procurement.[1] Grafts are obtained using commercially available harvesters that provide donor and recipient tubes to form press-fit implants.[14] The correctly sized harvester is positioned perpendicular to the donor site and advanced to a depth of approximately 12 to 15 mm into the underlying subchondral bone. The donor plug is carefully extracted so as to not shear the cartilage surface. Then, attention is turned to the recipient tunnel, where the recipient socket is advanced to approximately 2 mm less in depth than the donor plug. Once the recipient socket is formed, the donor graft is press-fitted gently into place. The plug is then seated with a tamp, using appropriate force to avoid chondrocyte damage and death[14] and leaving the plug flush with the neighboring articular cartilage (**FIGURE 5**).

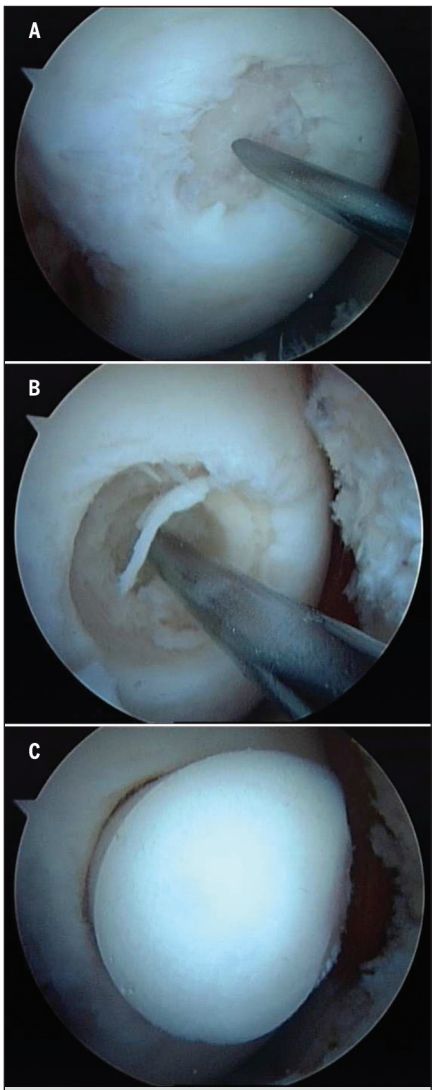

FIGURE 5. Osteochondral autograft transplantation of a medial femoral condyle defect in a right knee. (A) Arthroscopic view of the debrided lesion with a guidewire placed in the center of the prepared defect. (B) Recipient tunnel preparation. (C) Donor plug inserted into recipient tunnel.

Postoperative guidelines for motion and weight bearing include the use of a CPM device for 6 to 8 hours per day, beginning at 0° to 40° of flexion, set at 1 cycle per minute, and increasing 5° to 10° daily, with the goal of 100° of flexion by week 6. Patients must abstain from weight bearing for 6 weeks. Patients use a brace locked in full extension for the first week, then the brace is opened in 20° increments as quadriceps control is regained, with the goal of removing the brace by week 6. Patients progress to full weight bearing after week 6, with the goal of 130° of flexion. After week 8, patients may return to advanced activities. This combination of passive then active motion allows for optimal graft incorporation and healing.

Hangody et al[27] reported good to excellent results with osteochondral autograft in 92% of patients with femoral condyle defects and in 74% of patients with patellar defects. Additional studies report good to excellent outcomes of osteochondral autograft in 93% of talar dome lesions.[27] Emerging studies have evaluated osteochondral autografts in other joints, and supportive outcomes have been reported for the elbow.[4]

Osteochondral Allograft Transplantation

Osteochondral allograft transplantation uses fresh, cold-preserved cadaveric donor tissue (mature articular cartilage) to repair lesions larger than 2 cm^2 without the risk of donor site morbidity. Disadvantages of this procedure include graft availability, cell viability (reliant on the correct preparation and preservation technique of graft tissue), and risk of disease transmission. The majority of osteochondral allografts used are fresh rather than frozen. Fresh allografts are procured and stored in a physiologic medium at 4°C to preserve chondrocyte viability. Studies have shown cell viability after the graft has been stored for 14 days to range from 80.2% to 91.2%,[5] with exponential decreases that become unacceptable 28 days after procurement (cell viability of 28.9%).[66] Hence, the current recommendation is that a freshly procured os-

teochondral allograft tissue be used soon after 14 days of storage.[65]

Osteochondral allograft transplantation can be done arthroscopically but more often requires an arthrotomy.[14] The diameter of the lesion is approximated to a cannulated sizing cylinder, and the defect site is transformed to a recipient socket of a uniform depth of 6 to 8 mm,[14] which allows for maximal graft integration and minimal immunogenic response. A cylindrical instrumentation system is used to harvest the donor bone plug from the allograft. Prior to implantation of the osteochondral donor plug, the tissue is thoroughly washed using a pulsatile lavage to decrease and eliminate remaining bone marrow elements and reduce the risk of disease transmission and graft immunogenicity. Strong et al[61] showed a postoperative increase in recipient human leukocyte antigen antibodies. Any immune reactions that may occur are self-limited and differ from patient to patient. Phipatanakul et al[50] demonstrated that patients may or may not generate antibodies.[61] The cleaned graft is aligned and press-fitted into the recipient socket and lightly impacted using an oversized tamp. The senior author (B.J.C.) prefers to use a supplemental bioabsorbable screw (Arthrex, Inc, Naples, FL) or metal compression screw to ensure postoperative fixation.[14] This refined procedure yields a secure allograft with a contour nearly identical to that of the adjacent host articular cartilage (**FIGURE 6**).

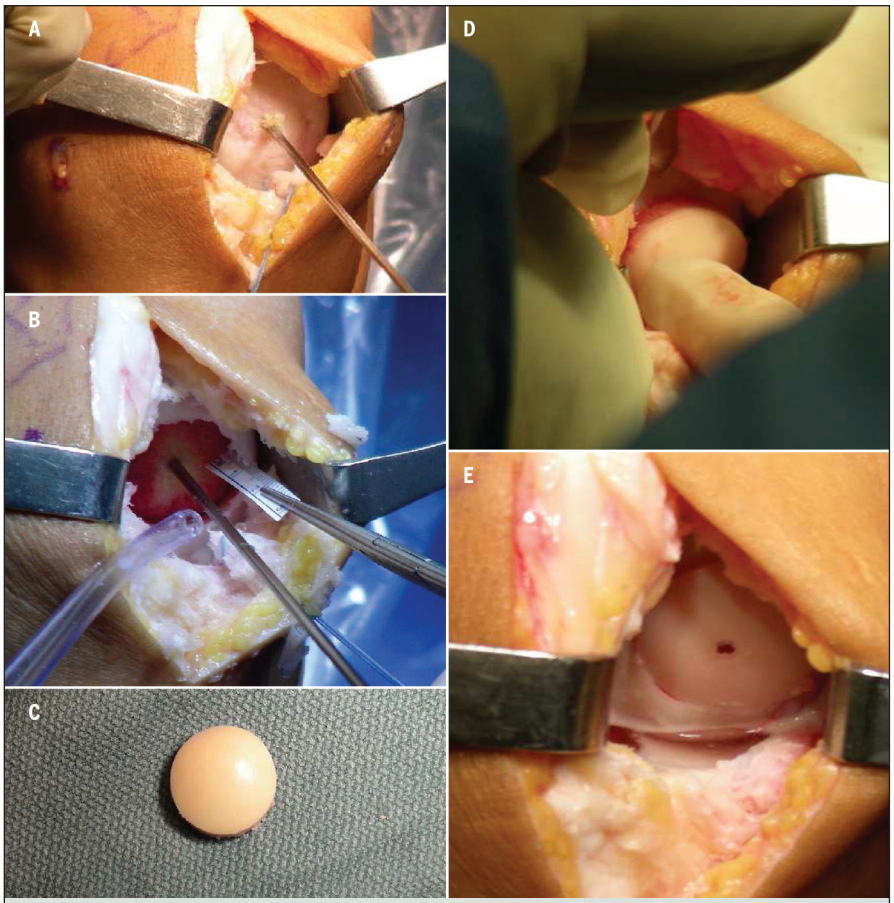

FIGURE 6. Osteochondral allograft transplantation in a right-knee medial femoral condyle (MFC) defect. (A) MFC lesion with centered drill guide. (B) Recipient socket with stable vertical walls created and measured for donor plug implantation. (C) Osteochondral allograft plug cut at appropriate depth. (D) Press-fit of donor plug into recipient socket. (E) Hole drilled in center of graft for bioabsorbable screw implantation.

Postoperative guidelines indicate that the patient should be non–weight bearing for the first 6 weeks. Immediately after surgery, patients are started on a CPM device for 6 to 8 hours per day, ranging between 0° and 40° and increasing by 5° to 10° increments daily, with the goal of 100° of motion by the end of week 6. The patient also wears a brace locked in extension for the first week. The brace is gradually opened during the next 3 weeks as quadriceps control is regained. After week 6, the patient can begin partial weight bearing and work to obtain 130° of flexion by the end of week 8. The patient can slowly return to full weight bearing between weeks 8 and 12. The patient then progresses to a pain-free full range of motion and normalized gait pattern. These weight-bearing restrictions allow an optimal balance between loading and resting the joint to provide mechanical stimulation for chondrocyte growth and orientation. If these strict guidelines are not followed, premature overload can culminate in subchondral collapse. Patients may resume unrestricted low-demand activities within 3 to 4 months and return to appropriate sports and high-demand activities within 6 months. High-impact sports are not recommended due to the uncertainty of possible collapse of subchondral bone or graft deterioration.[29]

Younger patients with unipolar lesions and a small defect size have the best outcomes, while higher failure rates are usually seen in patients with joint misalignment and osteochondral dissecans lesions.[29] Current evidence suggests that between 75% and 85% of patients who underwent osteochondral allograft transplantation experienced a subjective improvement.[14,29] Proper selection of patients for osteochondral allograft transplantation is paramount for success in cartilage restoration procedures.[20]

Emerging Future Techniques

Each surgical intervention previously discussed presents with limitations that have driven advancements in cartilage tissue engineering. These techniques create an artificial environment that allows

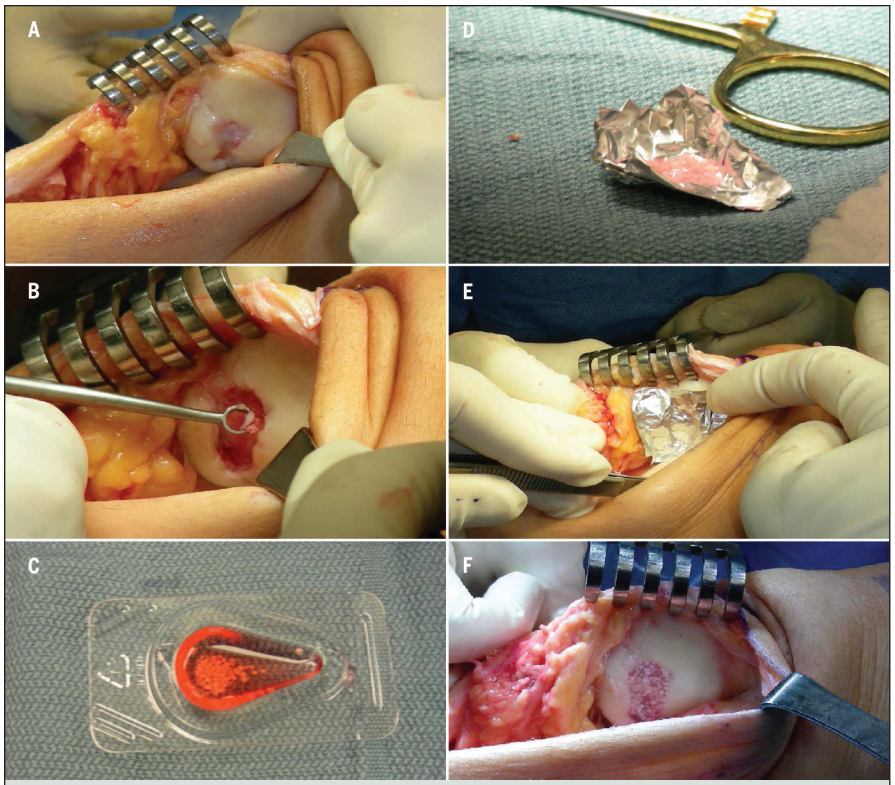

FIGURE 7. DeNovo NT Natural Tissue Graft (Zimmer, Inc, Warsaw, IN) implantation into a patellar chondral defect in the patella of the right knee. (A) Focal patellar chondral defect. (B) Preparation of the chondral defect with curette. (C) Juvenile minced cartilage in media. (D) Juvenile minced cartilage placed onto aluminum foil. (E) Minced cartilage implanted into defect using aluminum foil. (F) Minced cartilage with fibrin glue in place.

cells to construct a hyaline-like extracellular matrix that mimics the properties of native hyaline cartilage. The newest procedures use a minced cartilage technique, harvesting small pieces of healthy articular cartilage from allogenic or autogenic donors and implanting the tissue at the chondral defect site. This technique, DeNovo NT Natural Tissue Graft (Zimmer, Inc, Warsaw, IN), parallels the procedure of an ACI but provides juvenile allograft donor chondrocytes with their surrounding matrix and is performed in a single step.

At the time of surgery, the defect site is debrided of scar tissue, and vertical walls of native healthy cartilage are constructed. Next, the defect site is mapped onto sterile aluminum foil. Mincing the allograft tissue helps with cell migration and allows the final construct to be shaped appropriately to the defect site. The minced tissue is carefully transferred onto the mapped foil and coated intraoperatively with fibrin glue to form a cartilage-fibrin construct. The construct is carefully implanted in the defect site with additional fibrin adhesive (**FIGURE 7**). More than 70 clinical cases have been completed in clinical trials to date, but further assessment of patient outcomes needs to be performed.[40]

The DeNovo ET Engineered Tissue Graft (Zimmer, Inc) and Cartilage Autograft Implantation System (CAIS; DePuy Mitek, Inc, Raynham, MA) are alternative techniques currently under investigation. The DeNovo ET uses juvenile allogenic chondrocytes in culture to create a 3-dimensional sheet of cartilage,[2] while CAIS uses autogenic donor tissue that is procured from a non–weight-bearing region, minced, and implanted to the defect site on a scaffold placed into the defect. Both technologies are still under investigation and are about to undergo phase III clinical trial enrollment.

SUMMARY

The complex structure of articular cartilage and its inherently poor ability to repair itself make the treatment of partial- and full-thickness chondral defects challenging for scientists, surgeons, and physical therapists. These lesions may remain asymptomatic in many patients until they develop into a more clinically relevant problem requiring surgical intervention. Several techniques, such as palliative, reparative, and restorative procedures, can alleviate the patient's symptoms and improve functional outcomes. As innovations in cartilage restoration continue to develop, a specific treatment algorithm should be developed for each lesion type and requires a thorough clinical history and special consideration of the patient's age, lesion size, activity level, and postoperative expectations. In addition, the surgeon must address concomitant knee pathologies at the time of surgery or risk further progression of the chondral defect. Overall, each modality used to treat articular cartilage defects should be chosen specifically for each patient, because the procedure and rehabilitation are of utmost importance for successful long-term outcomes. Orthopaedic surgeons, physical therapists, and patients must work synergistically to attain positive clinical outcomes.

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