ADVANCED QUANTITATIVE IMAGING OF KNEE JOINT REPAIR
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PREFACE

Articular cartilage is avascular and has no intrinsic capacity to heal itself, and physical damage to cartilage poses a serious clinical problem for orthopedic surgeons and rheumatologists. No medication exists to treat or reconstitute physical defects in articular cartilage, and pharmacotherapy is limited to pain control. Over the last two decades, there have been numerous exciting developments in the surgical field of articular cartilage, meniscus and ligament repairs, and patients currently have a variety of treatment options. Magnetic resonance imaging (MRI) plays a critical role in pre-operative surgical planning, via its ability to identify the extent and severity of soft tissue lesions. There is high demand for advanced medical imaging technologies to identify patients who can be treated early and aggressively to prevent future morbidity. Further, it also plays an important role in post-operative management, by allowing surgeons to noninvasively monitor the morphological, biochemical, structural and biomechanical status of repaired tissue. Due to recent technological advances in high and ultra high field MRI and advanced biochemical and functional MRI techniques (T₂ mapping, delayed gadolinium enhanced MRI of cartilage (dGEMRIC), spin-lattice relation in rotating frame (T₁ρ) imaging, diffusion tensor imaging (DTI), chemical exchange saturation transfer (gagCEST) imaging, sodium MRI) have the potential to allow in vivo monitoring of the collagen and proteoglycan content of cartilage repair tissue. These techniques may provide useful biochemical, structural biomechanical metrics for next generation musculoskeletal tissue regeneration in general and cartilage injury, cartilage restoration, rehabilitation and knee joint function in particular.

The book consists of 11 chapters that offer the comprehensive overview and assessment of different surgical technologies in this rapidly evolving field, role of advanced imaging of repaired soft tissue monitoring, post
Preface

surgical management, clinical applications in regenerative medicine and potential future developments including prevention strategies. Chapters 1 and 2 specifically focuses on surgical and radiological techniques for clinical and morphological assessment of ligament, menisci, cartilage repair strategies, post-surgical evaluation and monitoring. In Chapters 3–9, the authors focused on advanced imaging techniques for biochemical, structural assessment of soft tissue repair, evaluation and monitoring. Lastly, the Chapters 10 and 11 provide state-of-the-art biomechanical and tissue engineering approaches of new therapies, management and prevention strategies. Each chapter is written by world leaders in their specialized fields of research. This book extensively covers the advanced quantitative imaging methods from a diversified multi-disciplinary research fields from, orthopedic surgeons, imaging physicists, biomedical imaging scientists, radiologists, mechanical engineers, tissue engineers and clinician scientists. We believe that this book will serve as a reference book for number of investigators working from basic science (preclinical) to clinical translation (bed side).

Finally, we take this opportunity to thank all the authors for contributing chapters related to their current research work that explain the state of the art “Advanced Quantitative Imaging of Knee Joint Repair”. Thanks to our QMMIG students, post doctoral fellows and collaborative faculty who incessantly provided us with the necessary academic stimulus to go on. We are also grateful to VK Sanjeed and Maranda Ward of world scientific publications for their constant support toward this project

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CHAPTER 1

SURGICAL TECHNIQUES FOR KNEE JOINT REPAIR

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Introduction

As the number of people participating in organized sports has increased in recent years, so has the incidence of sports related injuries. This increased participation in organized athletics has been found in school children, all the way up to “weekend warrior” athletes. It has been estimated that 30 million children in the United States participate in organized sports. In 2009, Darrow et al. specifically looked at high school athletes and found the incidence of sports-related injuries approached 40% of all non-fatal, unintentional injuries among high school youth treated in emergency departments. Of all the injuries reported in their cohort, it was found that the most commonly injured body site was the knee, which accounted for 29% of total cases. Other injury types included in this study were accidents involving the head (6.8%), shoulder (10.9%), wrist (4.3%), finger/hand (7.9%), and ankle (12.3%). It was found that of the reported injuries that required surgical intervention, more than half (53.9%) involved the knee.

Knee injuries in sports related accidents account for millions of visits to emergency departments each year. The most common knee injuries sustained by athletes include anterior or posterior cruciate ligament ruptures, medial or lateral meniscal injuries, cartilage injuries, and collateral ligament injuries. These injuries have a myriad of different treatment
strategies with the goal of returning the patient to their prior level of function and sport. This chapter will focus on the surgical management of these pathologies. We will specifically discuss epidemiology, anatomy, mechanism of injury, diagnostic work up, surgical options, and surgical outcomes.

**Anterior Cruciate Ligament Injury**

**Anatomy**

The anterior cruciate ligament (ACL) originates from the medial wall of the lateral femoral condyle and courses anteriorly and medially to insert into the tibial articular surface. It is composed of two functional bundles, the anteromedial and posterolateral bundles, named based on their tibial insertion sites. The specific locations of these attachments plays an important role in the biomechanics of the ACL. Due to the large attachment sites, the ACL allows different portions of the ligament to tighten at various degrees of knee flexion. The femoral attachment site is located on the posteromedial surface of the intercondylar notch on the lateral femoral condyle. The attachment is circular, spanning an area of approximately 113 mm$^2$. The tibial attachment is located approximately 15 mm from the anterior border of the tibial articular surface, covering an area of about 136 mm$^2$. The mid-substance cross-sectional area is approximately 40 mm$^2$ (Figure 1).3

**Biomechanics**

The function of the ACL is to provide primary anteroposterior stability and secondary rotatory and coronal stability to the knee joint.4,5 There is age related loss of strength of the ACL, with older ACLs failing with lower loads than younger ACLs.6,7 The ACL withstands a wide range of forces ranging from 100 N during passive range of motion exercises to about 1700 N during cutting, and pivoting maneuvers.8 The maximal tensile load is 2160 N.6

**Epidemiology**

The ACL is the most commonly injured ligament in the knee. It is most commonly injured during sports related activity with only a minority of
Fig. 1. Sagital view of cadaver knee showing anteromedial and posterolateral bundle of ACL. ACL runs from medial aspect of lateral femoral condyle to tibial spine.

ACL injuries occurring in high-energy trauma or activities of daily living.\textsuperscript{8} ACL injuries represent approximately 40–50% of all knee ligament injuries. Patients report hearing or feeling a pop at the time of injury 70% of the time and almost all patients notice swelling of the knee within 24–48 h of injury. The sports most commonly associated with ACL injuries are those that involve cutting or pivoting, namely soccer and skiing. Female athletes have a two to four fold higher risk of ACL injury than males.\textsuperscript{9}

\textit{Pathoanatomy}

The majority of ACL injuries are complete disruptions. In skeletally mature patients, the most common site of the disruption is midsubstance or along the femoral insertion of the ACL. In skeletally immature patients, avulsion off the tibial attachment with or without a piece of bone is more commonly seen.

\textit{Work up}

The first step to diagnose and treat an ACL injury is a thorough history and physical examination. Any patient with knee swelling after a sports
related knee injury should be evaluated for possible ACL tear. Diagnosis of chronic ACL injury may involve a history of recurrent knee pain, mechanical symptoms from a secondary meniscal tear or instability. A thorough history may be difficult in the acute setting due to pain and swelling associated with the injury. Patients with acute ACL injury present with a large effusion, related to hemarthrosis secondary to bleeding from the vessels within the ligaments synovial sheath. Palpation of all bony prominences should be carefully performed with special attention to the femoral origin of the medial collateral ligament. Patellar apprehension must be noted, as acute patellar dislocations often present with a similar history as ACL injury. The quadriceps and patellar tendons should also be examined as injuries to these structures may be confused with ACL injuries. Special testing for ACL injuries include the Lachman test, anterior drawer test and pivot shift test. The Lachman test is the most useful in the initial diagnosis. A sense of increased tibial translation or a lack of a solid endpoint are indicative of ACL injury. The pivot shift test is pathognomonic for ACL injury. The test begins with the knee in full extension, and the knee is the flexed while applying a valgus moment. As the iliotibial band (ITB) passes posterior to the axis of knee rotation at approximately 15° of knee flexion, the tibia (which is subluxated anteriorly on the femur) reduces with a visible shift at the lateral joint line. This should always be compared with the contralateral side, where a physiologic pivot shit or pivot glide may occasionally be present.

**Imaging**

Radiographic evaluation of a patient with a suspected ACL injury includes plain radiographs of the affected knee to rule out fracture in the acute setting. Associated injuries that may be identified on plain imaging include a Segond fracture\(^\text{10}\) (lateral capsular avulsion) and tibial eminence avulsion fractures in skeletally immature patients. Additionally, the presence of open physes is of particular importance as this can impact the surgical treatment approach. MRI is not required for the diagnosis of ACL injury, but it is useful for assessing for associated injuries to the meniscus, other ligaments, the articular surface and for the presence of subchondral bone marrow edema lesions and fractures. The characteristic edema pattern seen on MRI
Fig. 2. (A) T1 weighted sagittal MRI showing ruptured ACL. (B) T2 weighted sagittal MRI showing characteristic bone edema seen after ACL tear.

with bone marrow lesions present within the posterolateral tibial plateau and the central lateral femoral condyle correspond to the pivot-shift type translational event that occurs during injury (Figure 2). In the coronal and sagittal MRI images, disruptions in the normal black ACL fibers signify ACL injury.

**Treatment**

ACL reconstruction is indicated in active patient populations who are involved in cutting, pivoting and twisting activities. The goal of ACL reconstruction is to return functional stability of the knee to allow for return to full activity as well as to prevent further damage to the menisci and chondral surfaces that can lead to early-onset arthritis. Elderly or more sedentary individuals may have a good outcome with non-surgical management. Non-surgical management involves rehabilitation to strengthen the hamstrings (HSs) and quadriceps, as well as proprioceptive training. Activity modification is an important part of non-surgical management. Contraindications to surgery include: lack of quadriceps function, significant comorbidities, or inability to tolerate surgery or the necessary post-operative rehabilitation required.

The success rate of ACL reconstructions has reached up to 90% with respect to post-operative knee stability and patient satisfaction. Graft
choice varies from surgeon to surgeon. Multiple factors are involved in the choice of ACL reconstruction graft type, including biomechanical properties, biologic incorporation, associated donor site morbidity, graft tensioning issues, graft fixation options, and clinical outcome. Available graft options can be divided into two main classes: autograft and allograft. In these classes, autograft options include bone-patellar tendon-bone (BPTB), quadriceps tendon, quadrupled semitendinosus and gracilis HS tendon. Allograft options include quadriceps, Achilles, tibialis anterior or posterior, BPTB, and HS. The gold standard is thought to be BPTB autograft due to ease of harvest, comparable structural properties to the native ACL, available rigid fixation techniques, bone to bone rather than soft tissue to bone healing, and a long track record of success.\textsuperscript{12–14} Graft healing involves both the healing at the graft attachment site as well as the process of graft revascularization and incorporation (termed ligamentization). Grafts containing bone typically resemble fracture healing with bone healing occurring within six weeks. Soft tissue grafts take longer, between eight and 12 weeks to heal into host bone. The process of graft incorporation begins with a period of inflammation in which the graft loses strength and stiffness. This phase is between day 20 and up to 3–6 months after surgery, losing up to 80\% of its strength.\textsuperscript{15} Donor site complications are typically seen with BPTB grafts, include patellar fractures,\textsuperscript{16} patellar tendon ruptures,\textsuperscript{17} localized numbness and tendonitis.\textsuperscript{18} Use of allograft produces decreased donor site morbidity, shorter operative time, preservation of extensor and flexor mechanisms, and wide availability for cases involving multiligament injuries. Allograft ACL reconstructions have become popular in the treatment of patients older than 40 years of age (Figure 3). 

Technical aspects of ACL reconstruction involve proper tunnel positioning, graft tensioning and initial fixation and strength. In order to restore adequate anteroposterior stability, there must be adequate tensioning of the graft, however this has been largely an unquantifiable measure due to variability in graft choices, fixation techniques, positioning of knee flexion and knee rotation during tensioning. The reproducibility of tensioning has been questioned as most surgeons do this manually and the applied force can vary significantly from surgeon to surgeon. It is recommended that between 40 and 60 N of force be applied at near-full extension for tensioning.
Fixation methods have been widely studied and there is extensive literature addressing this issue, as rigid fixation of the ACL graft is one of the most important factors determining long-term success of the operation. Options for fixation include interference screws of different materials, staples, and suture tied over buttons or screws. Fixation problems typically occur on the tibial side. This may be due to decreased bone quality of the tibial metaphysis, tunnel orientation in relation to forces the graft experiences and the direction the tibial fixation must occur.\textsuperscript{19-21}

**Outcomes**

ACL reconstruction has generally excellent outcomes with more than 90% of treated patients returning to their previous level of activity. Autograft choice or one versus two incision technique do not appear to affect the outcome. Re-rupture rates vary from 2\% to 5\%.\textsuperscript{22} Studies have shown the instrumented laxity with KT 1000 arthrometer demonstrate 75–97\% of patients have <3 mm of side to side difference in laxity.\textsuperscript{23} Complications include those related to anesthesia, infection, knee stiffness, venous thromboembolism, painful hardware, and loss of terminal extension.

The stability of the ACL reconstruction is of upmost importance. Using instrumented Lachman’s test with the KT 1000 arthrometer, we are able to measure the stability of the ACL construct. Side to side comparisons between 0 and 2 mm are considered stable. Laxity greater than 5 mm is
considered unstable and a failure of reconstruction. Clinical studies have reported both low and high stability results for both allograft and autograft. A recent meta-analysis showed a significantly greater stability of autograft compared to allograft.\textsuperscript{24} Failure rates have also been reported as high as three times greater in allograft than autograft. BPTB autografts have significantly lower failure rates than BPTB allografts.

Recovery time can be defined as early postoperative and overall recovery time. Patients with allograft have faster early postoperative recovery because of the assumption that donor site morbidity is avoided. This is more apparent when comparing allograft to HS autograft.\textsuperscript{25} When comparing overall recovery time, autograft has the advantage. This is due to the slower revascularization of allografts, which makes surgeons assign them slower rehabilitation protocols.\textsuperscript{26}

Important factors for determining successful ACL reconstruction is correct femoral and tibial tunnels without PCL and roof impingement and the use of slippage-resistant, stiff strong fixation. Positive outcome is also associated with the patients ability to undergo brace-free, aggressive rehabilitation that is self-administered at home. Less important factors are the type of graft used, the use of a brace or immobilizer and the use of formal physical therapy.

**Posterior Cruciate Ligament Injury**

**Introduction**

In contrast to ACL rupture, posterior cruciate ligament injuries are relatively infrequent. In the past, this has led to limitations in clinical studies and a general lag in basic science and clinical research that is typically present for other ligamentous injuries. As new interest in this topic has developed, our understanding has improved and treatment algorithms have evolved. As put forth by Fanelli \textit{et al.}, PCL injuries are more common than initially thought, comprising 3\% of all knee injuries and being present in 37\% of trauma patients with acute hemarthroses.\textsuperscript{23} The overall incidence in the literature has been reported to be from 1\% to 40\% in acute knee injuries, which has been shown to be dependent on the patient population studied. Although PCL injuries can occur in sports related injuries, they are, more common in trauma patients.\textsuperscript{27}
Anatomy

The PCL is the primary restraint to posterior translation of the proximal tibia and plays an integral part to the overall stability of the knee. It also serves as a secondary restraint to varus, valgus and external rotation forces. The ligament is comprised of two inseparable bundles (anterolateral bundle (ALB)/posteromedial bundle), and originates from a broad, crescent-shaped area on the anterolateral aspect of the medial femoral condyle within the intracondylar notch and inserts into the PCL fossa. The PCL fossa is located posteriorly, between the two tibial plateaus. Although the bundles are inseparable, they have different functions that allow the PCL to resist posterior translation in both extension and flexion. The ALB makes up the bulk of the ligament and is taut at 90° of flexion and loose in extension, whereas the posteromedial bundle (PMB) is taut at 30° of flexion and loose at 90° of flexion (Figure 4).

Traditionally, as little was understood regarding the biomechanics and treatment of PCL deficient knees, patients who were found to have isolated PCL injuries were generally treated conservatively with physical
therapy and bracing. This treatment algorithm has changed towards surgical intervention as the anatomy and biomechanics have become better understood and new studies have shown that a large percentage of patients who have gone untreated develop late knee arthrosis affecting the medial and patellofemoral compartments.28

**History and physical examination**

Posterior cruciate ligament injuries often occur via a posteriorly directed force to the tibia (dashboard type injuries), as opposed to the non-contact mechanism that typically causes ACL tears. As these are generally high-energy injuries, they rarely occur in isolation, and are often seen in multi-ligamentous knee injuries. PCL injuries can also occur concomitantly with peri-articular fractures of the knee. In these instances, Kim et al. has reported that they are missed over 60% of the time, so one must have a high index of suspicion for PCL injury when evaluating patients with a fracture about the knee. In the patient with chronic PCL insufficiency, he or she often presents with remote history of trauma or fracture to the knee and complaints of anterior knee pain, difficulty with stair ambulation, or less commonly, instability.29

On physical exam, the posterior drawer test has been shown to most accurately assess for PCL injury. It has been reported to have a sensitivity and specificity of 90% and 99%, respectively.29,30 The grade of PCL injury is determined from the posterior drawer test findings (Table 1). The tibia must be positioned in its natural position to increase the accuracy of this exam, which involves the medial tibial plateau resting approximately 1 cm anterior to the medial femoral condyle. Once the knee is positioned appropriately, the examiner applies a posteriorly directed force to proximal tibia and looks for posterior translation of the tibia in relation to the

<table>
<thead>
<tr>
<th>Grade</th>
<th>Distance of posterior tibial translation (mm)</th>
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<tbody>
<tr>
<td>I</td>
<td>1–5</td>
</tr>
<tr>
<td>II</td>
<td>6–10</td>
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<tr>
<td>III</td>
<td>&gt;10</td>
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Surgical Techniques for Knee Joint Repair

Fig. 5. Posterior drawer done with the knee in 90° of flexion and posterior force applied to tibia.

An example of the posterior drawer test can also be seen below (Figure 5).

In addition to the posterior drawer test, the Godfrey posterior sag test and quadriceps active test are helpful adjuncts. The dial test can be used to evaluate for concomitant injuries to the posterolateral corner (PLC). Increased external rotation at 30° and 90° of flexion suggest a combined PCL and PLC injury.

Imaging

Once a PCL injury is suspected by history and examination, imaging must be obtained to confirm the diagnosis. Plain radiographs are performed to assess for posterior tibial subluxation, posterior tibial slope, avulsion fractures, and tibial plateau fractures. Varus malalignment is common in chronic PCL injuries and so if suspected, long leg alignment films can be obtained to assess the overall mechanical axis of the limb. Stress radiographs have been described as a way of differentiating between complete and partial PCL tears.

Magnetic resonance imaging (MRI) has become the preferred imaging test of choice when a PCL tear is suspected. Reports have shown that it can have a sensitivity of up to 100% in the diagnosis of acute PCL tears, however, has been found to be less accurate in the diagnosis of chronic PCL tears. Another advantage to MRI as the imaging modality of choice is that it offers information on the menisci, articular cartilage, and other ligaments within the knee, all of which can impact the treatment plan (Figure 6).