ELSEVIER
SAUNDERS

Orthop Clin N Am 36 (2005) 469–484

ORTHOPEDIC
CLINICS
OF NORTH AMERICA

The Indications and Technique for Meniscal Transplant

Winslow Alford, MD[a], Brian J. Cole, MD, MBA[b,*]

[a]West Bay Orthopedics, 120 Centerville Road, Warwick, RI 02886-6919, USA
[b]Rush University, Section of Sports Medicine, 1725 West Harrison, Suite 1063, Chicago, IL 60612, USA

Meniscal allograft transplantation (MAT) has moved into mainstream orthopedics. With proper patient selection, and recognition and treatment of comorbid conditions, MAT offers a solution that can at least temporarily decrease pain and increase function. This article reviews the basic science of meniscal mechanics, the pathomechanics of meniscal injury, and MAT indications and techniques. A brief description of treatment of comorbid conditions and the outcomes of MAT is also provided.

Meniscal anatomy and biomechanics

In a healthy knee, the medial and lateral menisci contribute to the health and mechanical protection of articular cartilage and help prevent degenerative joint disease. Removal of or injury to menisci has been implicated in articular degeneration and the development of osteoarthritis [1]. Articular cartilage damage has been shown to occur as early as 12 weeks after meniscectomy in skeletally mature mongrel dogs [2]. The many functions of the menisci include shock absorption, load transmission, secondary mechanical stability, and joint lubrication and nutrition [3].

Menisci are semilunar, wedge-shaped structures that enhance tibial-femoral joint stability by filling the void created by the incongruous femoral condyles and tibial plateau [4]. The lateral meniscus forms a *C*-shaped incomplete semicircle, whereas the medial meniscus is more *U* shaped with a wider separation of its anterior and posterior horns than in the lateral meniscus. By deepening the tibial socket, menisci act as secondary stabilizers—particularly the posterior horn of the medial meniscus, which blocks anterior translation of the tibia on the femur [5–8]. Loss of the posterior horn of the medial meniscus in the setting of primary anterior cruciate ligament (ACL) reconstruction has been associated with graft elongation and joint laxity [9,10], which may ultimately accelerate osteoarthritis in the ACL-deficient knee [5,11].

During the normal gait pattern, the articular surface of the knee bears up to six times the body weight, with over 70% of that load borne by the medial tibial plateau [12,13]. The menisci increase the contact area and dissipate the compressive forces at the articular cartilage. The lateral meniscus carries 70% of the lateral compartment load, compared with just 40% by the medial meniscus [14]. By converting joint-loading forces to radial-directed hoop stresses on circumferential collagen fibers, the menisci transmit 50% of the joint load when the knee is in extension, and 90% when the knee is in flexion [15,16]. Meniscal loss increases peak articular contact stresses and can lead to the development of early degenerative changes [15,17,18]. Loss of just 20% of a meniscus can lead to a 350% increase in contact forces [19]. MAT with bone anchorage of the anterior and posterior horns improves contact forces compared with total meniscectomy [18,21,29] and can protect articular cartilage [22,23].

Meniscus ultrastructure

Meniscal tissue is composed of elongated cells on the surface and ovoid cells in deeper layers that are equipped with few mitochondria, suggesting anaero-

* Corresponding author.
E-mail address: bcole@rushortho.com (B.J. Cole).

doi:10.1016/j.ocl.2005.05.003

bic metabolism [19]. The extracellular matrix of menisci is 74% water by weight, but type I collagen comprises about 65% of the dry weight, and glycosaminoglycans make up 2% of the dry weight. Other collagens (types II, III, V, and VI) make up about 5% of the dry weight. Elastin, fibronectin, and thromboplastin assist in organizing the matrix by binding molecules. This blood supply of a meniscus is key to successful meniscal repair or transplantation. The inferior medial and lateral geniculate arteries form a plexus encompassing 10% to 30% of the width of the medial meniscus and 10% to 25% of the width of the lateral meniscus [24], combined with a 1- to 3-mm cuff of vascular synovium. Synovial fluid is pumped through a network of micropores during normal joint motion, providing nutrition to articular cartilage [25].

Meniscal tissue is structured as a fiber-reinforced, porous-permeable composite material containing solid (matrix proteins) and fluid (water) [26,27]. Circumferential peripheral collagen bundles act as structural scaffolding of the meniscus, provide hoop stress resistance to strain, and provide increased stiffness. In contrast, the central two thirds has randomly oriented collagen fibers and a sheetlike arrangement of radial tie fibers, with correspondingly higher strain rates and less stiffness [28]. The restraining collagen fibers, if undamaged, permit little swelling in the stiff peripheral region. The less-stiff central region has a high proteoglycan/collagen ratio that promotes hydration and swelling, enabling the meniscus cartilage to load-share with the articular cartilage. Abnormal meniscal hydration pressure indicates collagen or proteoglycan damage.

Collagen and proteoglycan damage can be caused by mechanical factors (tears or surgical resection), enzymatic degradation, or synthesis of new, poorly functioning molecules. Collagen damage leads to abnormal hydration and an irreversible cascade of tissue alteration. When proteoglycans are damaged (but the collagen remains intact), these tissue changes are reversible. For example, immobilization leads to proteoglycan loss, which is reversed after a return of motion stimulates fibrochondrocytes to synthesize new proteoglycan molecules. Central and peripheral tears occur with different mechanisms and have different consequences. With its higher strain rate and lack of stiffness, central meniscus collagen meshwork tears are common (bucket handle tears), often with low-energy mechanisms. Reparability depends on the location and orientation of the tear. The consequence of central tissue resection is far less than that of peripheral meniscal resection. Hoop-strain resistance to joint compression of the meniscus relies on an intact periphery, and tears that violate the peripheral rim can render that compartment meniscus deficient, wherein meniscal allograft transplantation (MAT) may be indicated [29].

These principles also apply to a transplanted meniscus. If a meniscus is transplanted into a degenerative compartment with Fairbank changes [30] or an inflammatory [31] environment, then the allograft will fail as did the native meniscus. Circumferential collagen bundles in the allograft must be intact from anterior to posterior horn with secure bone fixation [18,21,32], using either bone plugs or a slot and keyhole technique. Physiologic loads will stimulate the fibrochondrocytes. Proper load-sharing and congruent articulation require correct allograft size and position.

Effect of meniscectomy

Meniscal tears cause pain and dysfunction and predispose the knee to articular cartilage degeneration. The size, location, and orientation of the tear will determine if a torn meniscus retains its biomechanical function [22]. Meniscus tears are repaired when possible, but partial and total meniscectomies are still necessary, causing altered biomechanics and detrimental effects that have been recognized for decades [30]. The relationship between meniscectomy and degenerative changes is clear [33–38], particularly in the lateral compartment where unique biomechanical and anatomic factors lead to a higher risk for degeneration than in the medial compartment [15,16,18,39]. Under physiologic conditions, the lateral meniscus carries most of the load in the lateral compartment, whereas the medial compartment shares the load almost equally between the meniscus and the exposed articular cartilage [16].

Historical perspective of meniscal allograft transplantation

The first human joint transplantations occurred a century ago [40,41], but the first true MAT occurred in 1972 when Zukor and colleagues [42] reported on a series of 33 fresh MATs. Size-matching a donor to a recipient within narrow time constraints because of primitive allograft processing techniques [43] cause logistical challenges such as scheduling surgery with short notice. MAT has gained popularity, as the development of safe and effective allograft tissue preservation and storage techniques has allowed for the creation of an inventory of variously sized menisci, and its protective effect on articular cartilage has been demonstrated in rabbits [44]. Graft preparation and sterilization methods have been refined to optimize healing and revascularization rates [11,45,46], graft shrinkage [47–49], cellularity [50,51], and donor and host DNA levels [52].

Immunogenicity

Animal studies have not demonstrated a predictable humeral or cellular-based immunologic rejection response from bone allografts in rabbits [53] or implanted meniscal allografts in goats [52,54] or mice [55].

The most immunogenic portions of the meniscal allograft are the cellular elements of the cancellous bone anchors [56], but studies of even massive bone allograft implantation [57] demonstrated a low rate of clinically meaningful immunogenic reactions. IL-17, which is a recently discovered pro-inflammatory family of cytokines secreted by activated T cells, seems to be operative in disparate tissues such as articular cartilage, bone, and meniscus and other soft tissues of the body, and to play a role in the homeostasis of these tissues in their healthy state [58]. Although meniscal allograft rejection has been reported [59], most series have not reported significant sequelae related to immunologic rejection. De Boer and Koudstaal [60] implanted a nontissue-antigen–matched cryopreserved meniscal allograft in the lateral compartment of a patient's knee that remained metabolically active with excellent clinical results and did not differ from control specimens. van Arkel and colleagues [61] and Khoury and colleagues [62] reported antibodies against the HLA complex [56] using nontissue-antigen–matched cryopreserved meniscal allografts without accompanying graft failure.

Graft procurement and processing

Because of difficulties harvesting and distributing fresh donor allografts to a size-matched recipient within a few days of harvest, fresh menisci suitable for allograft implantation have given way to bank-preserved meniscal allografts. Stringent donor screening include a comprehensive medical and social history as a critical first step in ensuring disease-free allograft tissue. The American Association of Tissue Banks has defined the recommended testing protocol [63]. Serologic screening is performed for HIV p24 antigen, HIV-1/HIV-2 antibody, human T-lymphotropic virus 1 and human T-lymphotropic virus 2, hepatitis B surface antigen, hepatitis B core antibody, antibodies to hepatitis C virus, and syphilis. Most banks perform polymerase chain reaction (PCR) testing, which detects one HIV-infected cell out of 1 million cells. The current window of time for development of detectable antibodies to HIV is approximately 20 to 25 days (prior to that, a donor may be infected but test negative for HIV). Blood cultures for aerobic and anaerobic bacteria are conducted and lymph node sampling may be performed.

Graft processing, including debridement, ultrasonic/pulsatile washing, and use of ethanol to denature proteins, further lowers disease transmission risk. Freezing further lowers the risk, but HIV can survive washing, freezing, and freeze-drying [64]. Safety clearly depends on donor screening and not graft processing. The current risk for HIV transmission by frozen connective-tissue allografts is estimated to be 1 in 8 million [65].

The tissue is procured within 12 hours after death (fresh grafts) or within 24 hours after death if the body has been stored at 4°C. Currently, tissue may be harvested with the use of sterile surgical technique or it may be procured in a clean, nonsterile environment and secondarily sterilized. Harvested tissue is preserved by one of four methods: it can be fresh, cryopreserved, fresh-frozen, or lyophilized. Fresh and cryopreserved allografts contain viable cells, whereas fresh-frozen and lyophilized tissues are acellular at the time of transplantation. Fresh tissue is harvested under sterile conditions within 12 hours after death. The tissue is stored in a culture medium at 4°C or 37°C to maintain viable cells. Transplantation must be completed within several days of graft procurement, resulting in difficult logistics [66]. The exact rate and duration of cell viability is unknown. Jackson and colleagues [48] used DNA probes to demonstrate that all of the donor cells in a fresh meniscal transplant were rapidly replaced by host cells. Cryopreservation includes use of a cryoprotectant (ie, dimethylsulfoxide) to maintain cell viability and graft biomechanics [67]. Fresh-frozen grafts are rapidly frozen to −80°C, killing cells but maintaining material properties. Lyophilization, or freeze-drying, kills cells, affects graft material properties, and causes shrinkage [45,68]. Unlike fresh osteochondral grafts, the morphologic and biochemical characteristics of meniscal allografts do not depend heavily on cell viability. Therefore, the most commonly implanted grafts are either fresh-frozen or cryopreserved, and animal studies have shown no important differences between theses two methods [48,69].

Secondary sterilization with ethylene oxide, gamma irradiation, or chemical means may be used for fresh-frozen or lyophilized grafts. The amount of gamma irradiation required to eliminate viral DNA (at least 3.0 mrads [30,000 Gy]) may adversely affect the material properties of the meniscus [12]. Lower doses of gamma irradiation (<2.0 mrads [<20,000 Gy]) may be used for bacterial sterilization. Ethylene oxide is used only for lyophilized grafts, but it is not recommended because the ethylene chlorohydrin byproduct has been found to induce synovitis [70]. Chemical sterilization may be performed using proprietary bactericidal/virucidal solutions. In general, however, secondary sterilizing for meniscal allografts is not preferred.

Indications for meniscus transplantation

The ideal patient for meniscal allograft transplantation is a young but skeletally mature nonobese individual who has stable knee ligaments, normal anatomic alignment, and normal articular cartilage and is seeking treatment for pain in a meniscal deficient compartment. There must be no inflammatory arthritis, synovial disease, or history of infection in the involved knee. The patient should be too young for total knee arthroplasty. There is no upper chronologic age limit, but patients who have meniscal deficiencies and are in their mid-50s often have significant arthritis. Skeletal maturity is necessary to avoid causing asymmetric physeal arrest and progressive angular deformity.

To optimize the mechanical environment of the implanted meniscus, obesity should be a contraindication to meniscal transplantation. Untreated comorbidities of ligament instability, axial limb malalignment, and cartilage defects or degeneration also cause a hostile mechanical environment. These comorbidities can often be treated with simultaneous ligament reconstruction, osteotomy, or cartilage restoration. Even slight angular deviation compared with the contralateral limb may require an osteotomy. Concomitant or staged procedures is discussed later.

Fairbanks changes in meniscectomized knees range from the formation of an anteroposterior ridge projecting downward from the margin of the femoral condyle over the meniscal site to a generalized flattening of the marginal half of the femoral articular surface of the involved compartment, resulting in narrowing of the joint space on the involved side often associated with varus/valgus deformity of the knee [4]. Serious articular disease (ie, late grade III or IV) [71] and radiographic signs of flattening of the femoral condyle or marked osteophyte formation lead to poor graft survival, however, and are the most common contraindications to meniscal transplantation [72–74]. Restoration of the normal meniscal anatomy could decelerate or prevent degenerative change, but this is unproven. Systemic metabolic condition or local inflammatory condition affecting the knee is a contraindication to meniscal transplantation. Synovial disease or metabolic conditions will damage meniscal allografts. Immunodeficiency or a history of infection in the involved knee is a contraindication to meniscal transplantation, as the potential for devastating outcomes outweighs the potential for benefit of this procedure.

The surgeon must identify the specific motivation for a patient seeking transplantation and adjust expectations for partial, short-term pain relief. MAT could potentially retard osteoarthritis but it is primarily a pain-relieving effort. The patient should seek treatment for pain in the meniscal deficient compartment, and understand that at best, meniscal transplantation does not prevent the need for total knee arthroplasty.

Patient evaluation

After meniscectomy, patients report a gradual increase of joint-line pain, activity-related swelling, pain that changes with the ambient barometric pressure, and occasionally painful "giving-way" caused by quadriceps inhibition. A thorough history of the index injury and subsequent treatments, such as ligament reconstruction or management of articular cartilage lesions, are needed. Physical examination is essential to reveal malalignment, ligament deficiency, or articular cartilage lesions that would modify treatment plans. Patients generally have tenderness on the involved joint line often with a palpable osseous change at the femoral or tibial condyle. An effusion may or may not be present. For a patient to receive a transplant, range of motion must be normal.

Routine radiographs include weight-bearing anteroposterior view of both knees in full extension, a non–weight-bearing 45° flexion lateral view, and an axial view of the patellofemoral joint. A 45° flexion weight-bearing posteroanterior view can identify joint narrowing not seen on extension views [75]. Long-cassette mechanical axis films should be obtained if there is clinical malalignment. MRI techniques of two-dimensional fast spin-echo and three-dimensional fat suppression with and without intra-articular gadolinium can detail articular cartilage [76]. Three-phase bone scans are rarely used to detect increased uptake in the involved compartment.

Allograft sizing

The appropriate size of an absent meniscus cannot be determined by measuring the contralateral meniscus in the same compartment, as meniscal allografts are side- and compartment-specific, nor can the allograft size be predicted by a patient's height [77]. MRIs, radiographs, and CT scans have overestimated [78], underestimated [79], or in the case of CT arthrogram [74], over- and underestimated the size of meniscus allografts. Because of these potential inaccuracies, plain radiographs are most commonly used to size allografts [80,81]. Preoperatively, precise measurements are made on anteroposterior and lateral radiographs, with magnification markers placed on the skin at the level of the proximal part of the tibia. The surgeon should be familiar with the sizing techniques used by the tissue provider to minimize the chance of a size mismatch. Most commonly, the technique described by Pollard and colleagues [80] is used. The meniscal width is determined on an anteroposterior radiograph after correction for magnification. Meniscal length is calculated on the lateral radiograph on the basis of the sagittal length of the tibial plateau. Following correction for magnification, this length is multiplied by 0.8 for the medial meniscus and by 0.7 for the lateral meniscus. With use of this technique, size mismatch occurs less than 5% of the time. If the surgeon perioperatively judges the graft to be the incorrect size or compartment, the meniscus is not used. Small size mismatches can be handled with only minor modifications and are likely to have minimal effects on anatomic restoration, but accurate sizing is key to maximizing graft survival and chondroprotection [82].

Surgical techniques

Meniscal allograft transplantation replaces an absent or deficient meniscus in an anatomic position and restores the original meniscofemoral or meniscotibial articulation. The transplantation can be performed either open or with an arthroscopically assisted technique. The two methods have similar outcomes, but arthroscopic techniques are now routinely used because of the reduced surgical morbidity [45,72,83–89].

Meniscal allografts are anchored with either a bone bridge that rigidly fixes the distance between the anterior and posterior horns, or separate bone plugs on the anterior and posterior horns. For both techniques, the meniscus must be placed in an anatomic position with secure bone anchorage of the anterior and posterior horns [18,20,21]. The medial side may be anchored with either plugs or a bridge, whereas plugs are used only for medial transplants and not on the lateral side where the proximity to the anterior and posterior horns [90] risks tunnel communication. Using bone plugs on the medial side allows minor modifications to match the variable position of the anterior horn [77,91]. Proponents of a bone bridge on the medial side point out the ease of insertion and maintenance of the anatomic relationship between the allograft horns [86,92]. The decision to use a bridge or plugs on the medial side depends on surgeon preference.

Patient positioning and initial preparation

The patient is placed under general anesthesia and intravenous prophylactic antibiotics are administered. Before placing the patient in the desired leg holder, an examination under anesthesia is performed to confirm ligament stability. The patient is supine with the leg either unsupported with a lateral post placed just proximal to the knee, or placed in a midthigh leg holder with a tourniquet on but not inflated. The position of the leg holder should be proximal enough to allow ample exposure to the posterolateral and posteromedial corners for an inside-out meniscal repair, but distal enough to allow considerable valgus or varus stress to be placed on the knee without undue concern of a femur fracture. Standard arthroscopic portals are used and a diagnostic arthroscopy is performed to confirm the absence of significant chondral injuries in the recipient compartment, particularly if prior surgeries were performed by a different surgeon. The debridement of residual meniscal tissue should be performed without a tourniquet to verify a vascularized recipient meniscocapsular interface during debridement.

For both fixation techniques, the initial steps for medial and lateral meniscal transplantation are similar and are performed in the recipient compartment only. The host meniscus is debrided arthroscopically to a 1- to 2-mm peripheral rim until punctate bleeding occurs. A remnant of the anterior and posterior horns is left to clearly identify their location during tunnel creation (plugs) or slot formation (bridge). A low modified notchplasty on either the medial (protect posterior cruciate ligament [PCL]) or lateral (protect ACL) femoral condyle will facilitate allograft passage and visualization. A inside-out meniscal repair incision at the posterolateral or posteromedial corner is also used.

Bone plug technique

Separate bone plugs are often used to anchor the anterior and posterior horns of the medial meniscus. For this procedure, the involved compartment is prepared in the same manner as if performing a bridge technique. Two 9-mm cylindrical bone plugs are cored from the meniscal allograft, preserving all soft tissue attachment of the meniscal horns. No. 2 braided nonabsorbable polyethylene sutures are passed through 1.5-mm drill holes in each plug. The posterior horn bone plug can be undersized by 1 mm to facilitate passage and seating in the tunnel. A traction stitch in the posterior medial corner of the allograft will facilitate implantation (Fig. 1).

A modified low notchplasty between the fibers of the PCL and the medial femoral condyle will improve visualization and facilitate plug passage. To drill the recipient tunnels, an ACL tibial guide is used to pass a pin from the medial to the tibial tubercle to the exact center of the posterior horn, and reamed to 9 mm. The anterior horn is anterior to the footprint of the ACL at the anterior margin of the tibial plateau. The anterior tunnel is generally made after the meniscus is seated posteriorly and repaired peripherally with inside-out sutures.

Viewing from the lateral portal, the medial portal is expanded to receive the allograft. Next, the posteriomedial traction stitch is passed through the knee and out the posteromedial corner meniscus repair incision. The posterior bone plug stitch is then passed into the knee and out through the posterior horn tunnel using a suture passing device. Maintaining tension on the traction stitches at the posteromedial corner and posterior bone plug, a valgus stress is placed on the knee to open the medial compartment while the allograft is guided through the expanded

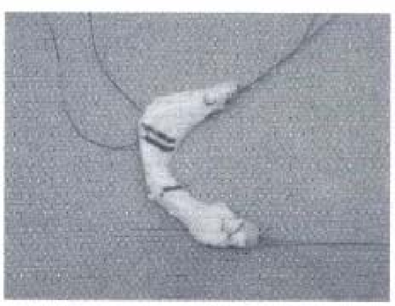

Fig. 1. Anchoring sutures are passed through each bone plug and a monofilament traction suture is placed into the posteromedial edge of the meniscus to facilitate reduction during implantation.

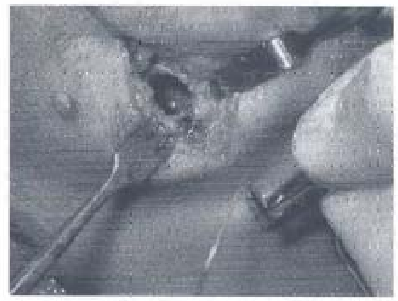

Fig. 2. The anterior horn plug is pulled into a blind-end tunnel at the anterior horn attachment with sutures passed through the anterior cortex.

medial portal and into the medial side of the joint. Positioning the bone plug in the posterior tunnel takes patience and persistence, but is facilitated by the low medial notchplasty and removal part of the medial tibial eminence, and by placing a valgus stress on the knee while pulling on the traction stitch with the knee positioned in about 30° of flexion. After the meniscus is reduced in the medial compartment, the knee is cycled several times to properly position the meniscus.

After the meniscus is secured posteriorly, the anterior horn bone plug is press-fit into a blind tunnel through the host anterior horn footprint. Sutures are passed through the anterior cortex of the proximal tibia with a free cutting needle and tied over bone (Fig. 2). This technique avoids an additional stress riser in the tibial metaphysis and does not interfere with a tibial ACL tunnel if a simultaneous ACL reconstruction is performed.

Eight to ten vertically placed 2-0 nonabsorbable mattress sutures are placed from posterior to anterior with use of a standard inside-out meniscal repair technique. On the medial side, all-inside bioabsorbable devices are a reasonable choice to secure the most posterior aspect of the meniscus to minimize the risk for neurovascular injury, but their pull-out strength is less than that of vertical sutures and they provide only single-point fixation [93,94].

Bridge in slot technique

Detailed descriptions of the bridge in slot technique are available elsewhere [85,86]. The slot is created directly in line with the anterior and posterior meniscal horns of the recipient compartment. A mini-arthrotomy is made either directly adjacent to the patellar tendon in line with the host anterior and posterior horns or by splitting the tendon. Arthro-

Fig. 3. Fluoroscopic lateral view is used to monitor location of reamer with respect to posterior tibia.

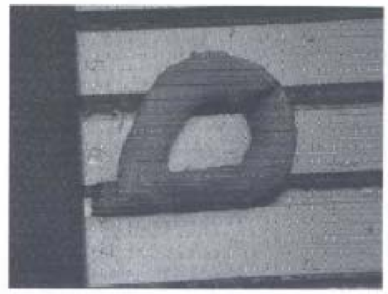

Fig. 5. The width of the lateral meniscus bridge measured carefully with the provided jig.

scopic electrocautery is used to mark a line between the centers of the horn footprints. Next, a 4-mm burr is used to create a superficial reference slot along this line. This reference slot should be the depth of the burr and should match the sagittal slope of the tibia. A depth gauge is placed into the slot and hooked onto the posterior tibia to confirm that it is of uniform height and depth, and to accurately measure the anteroposterior dimension of the slot. A drill guide chucked at the measured depth is used to insert a guide pin parallel to the tibial slope, taking care not to penetrate the posterior cortex of the tibial plateau. It is recommended that the guide wire placement and reaming be performed under fluoroscopic control (Fig. 3). The guide pin is advanced to but not through the posterior edge of the tibial plateau. An 8-mm cannulated reamer is advanced over the guide wire, and an 8 × 10-mm box cutter creates a slot. A rasp is used to assure uniformity in width and depth and to prevent impingement of the prepared allograft bone bridge.

Allograft preparation

The allograft arrives from the tissue bank as a hemiplateau with the meniscus attached. All non-meniscal soft tissue is removed and the exact location of the anterior and posterior horn anchors are identified (Fig. 4). Using a cutting guide, the bridge is then cut to 7 × 10 mm. The authors recommend undersizing the full length of the bridge by 1 mm to facilitate passage through the slot. The prepared bridge is tested for ease of passage though calibrated troughs on the back table (Fig. 5). The posterior wall of the bridge should be flush or slanted slightly anterior to the fibers of the posterior horn attachment to allow for insertion at the most posterior edge of the prepared slot. Bone anterior to the anterior horn should be left in place to allow for safer graft manipulation during insertion. An 0-PDS vertical mattress traction suture is placed at the junction of the posterior and middle thirds (Fig. 6).

Fig. 4. The thawed lateral meniscal allograft is prepared on the back table simultaneously with trough preparation in the lateral tibial plateau of the recipient. The unprepared allograft is an en bloc section of the meniscus and the hemiplateau, incorporating the anterior and posterior horns.

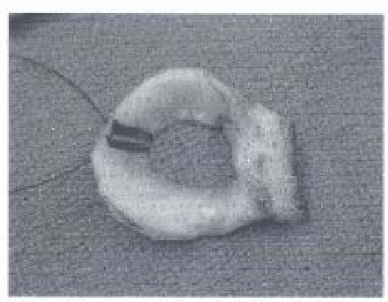

Fig. 6. The prepared bone bridge should have a minimal amount of bone posterior to the posterior horn insertion to avoid impingement leading to improper position of the posterior horn.

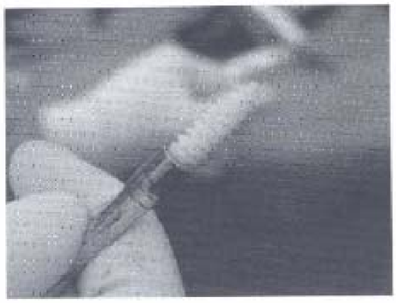

Fig. 7. An interference screw machined from allograft bone is used for fixation of the bone bridge in the slot.

To insert the graft, the traction sutures in the allograft are shuttled through the posterior incision using zone-specific meniscus repair cannulae. The allograft is inserted though the arthrotomy and aligned with the slot as the meniscus is reduced under the femoral condyle by pulling on the traction suture and cycling the knee to allow the femoral condyle to engage and position the allograft meniscus. Simultaneous varus or valgus stress will open the recipient compartment. The slightly undersized meniscal bone bridge allows the meniscus to achieve its proper position by sliding freely within the tibial slot. Once the proper bone-bridge position is achieved, a guide wire is inserted between the bone bridge and the more midline wall of the slot. A tap is used over the guide wire to create a path for an interference screw with the bone bridge held firmly in place by an elevator placed through the arthrotomy. A 7 × 20-mm or 8 × 20-mm bioabsorbable interference screw is inserted while maintaining meticulous rotational control of the bone bridge. Of particular importance is the fixation of the allograft bone bridge within the host tibial slot to maintain the proper anatomic position of the meniscal horns. There has been recent success with allograft interference screws created from cortical allograft bone (Fig. 7) [86]. However, bioabsorbable screws offer an acceptable alternative.

The final arthroscopic examination of the implanted allograft should confirm not only that the graft is anatomically reduced under the condyle but also that the proper size was selected. The lack of undulation on the surface indicates that the tissue is not distorted in situ (Fig. 8). The meniscus is then sutured as described in the bone plug technique.

Combined procedures

It is often advisable to perform simultaneous or staged procedures to treat comorbidities that may coexist in the setting of meniscal transplantation. Limb axis malalignment, ligament instability, or cartilage defects may require an osteotomy, ligament reconstruction, or a cartilage resurfacing procedure. When combining a meniscus transplant with other procedures, it is important to plan the exact sequence of events in a detailed pre-operative plan.

Corrective osteotomy

If the recipient compartment is under more than physiologic compression, realignment osteotomy should be performed as an adjunct procedure [95]. In the setting of medial meniscal deficiency and varus alignment, a combined meniscus transplantation and high tibial osteotomy should be performed. In contrast to a standard high tibial osteotomy for isolated medical compartment osteoarthritis, in which the aim is to correct the mechanical axis laterally to 66% of the width of the tibial plateau in the lateral compartment [96], high tibial osteotomies combined with medial meniscus should correct the mechanical axis to just beyond neutral. The authors recommend the use of an opening medial osteotomy to create a valgus correction, but the more traditional closing lateral osteotomy is also a reasonable option. Commercially available instrumentation (Arthrex, Naples, Florida) allows for a technically precise, simple, rapidly performed opening medial osteotomy with rigid fixation. In the less-common scenario of valgus angulation of a knee joint with lateral compartment disease, a distal femoral osteotomy is advisable. Generally the authors recommend an opening lateral distal femoral osteotomy with rigid plate fixation, although other techniques and fixation methods

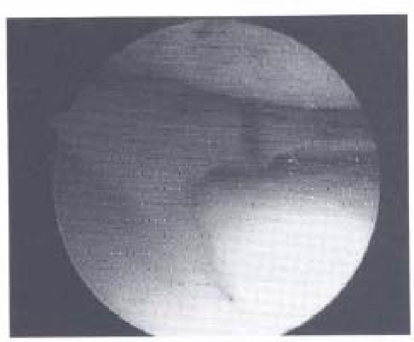

Fig. 8. Proper position, size, and suturing of the allograft under femoral condyle is evinced by the smooth contour in situ without undulations.

have been described, including a percutaneous dome osteotomy combined with temporary external fixation and intramedullary nail fixation [97]. For varus and valgus osteotomies, care must be taken not to overcorrect.

When performing a high tibial osteotomy with MAT, the bridge and slot technique will prevent communication of metaphyseal tunnels with the osteotomy. If bone plugs are used, the tunnels should exit as far proximal as possible to avoid traversing the osteotomy. Arthroscopic evaluation, soft-tissue preparation, notchplasty, and slot or tunnel creation of the meniscal transplant technique are performed before the osteotomy. Osteotomies should be performed as far distally as possible, and secure fixation of the osteotomy must withstand the valgus stress required for graft insertion and meniscal repair. Inserting osteotomy fixation hardware under fluoroscopic guidance is important to direct screws away from the meniscal tunnels or trough.

Meniscal allograft transplantation and anterior cruciate ligament reconstruction

Uncorrected ligamentous instability is a contraindication to meniscal transplantation. A preoperative evaluation of a meniscal-deficient knee includes a careful analysis of the ligamentous instability. This evaluation includes the history of injury, a familiarity with previous surgical procedures, MRI and radiograph information, and ideally, an arthrometric evaluation. An examination of the ACL under anesthesia is more reliable than while the patient is awake. Ideally, if a patient had prior surgeries, documentation of that exam would be available from those previous surgeries.

The biomechanical interdependence between an ACL reconstruction and the presence or condition of functional menisci is well documented [98]. A successful ACL reconstruction relies on an intact medial meniscus to minimize anterior-posterior stress [10,39], and an intact ACL, in turn, protects menisci and articular cartilage [99,100]. Simultaneous meniscus transplantation and ACL reconstruction have been shown to be mutually beneficial in properly selected patients [101,102].

If a meniscus transplant is combined with either primary or revision ACL, there are several issues to consider related to the three-dimensional relationship of tunnels in the tibial metaphysis. Prior tunnel expansion and position and intended locations of new tunnels (in the setting of revision ACL reconstruction), ACL graft selection, and meniscus anchor method offer variability to address the needs of each particular patient. With bone plug technique, all soft-tissue and osseous portions of the meniscal transplant technique are performed first. The tibial tunnel for the anterior cruciate reconstruction is then drilled slightly more medially than usual to avoid confluence between it and the tunnel for the posterior horn of the meniscus. The remaining portions of the anterior cruciate reconstruction are performed as usual. With a bone-bridge technique, the tibial tunnel for the anterior cruciate reconstruction is reamed after placement of the meniscal allograft. Placing the tunnel entrance slightly distally and medially on the tibia can minimize confluence between the tunnel and the lateral slot. The meniscal bone bridge may, however, be partially intersected without untoward effects during creation of the tibial tunnel [101]. Use of a hamstring graft for the reconstruction of the ACL may facilitate graft passage by allowing for a smaller-diameter tibial ACL tunnel.

Occasionally, patients have combined varus alignment, ACL deficiency, and an absent medial meniscus with intact articular cartilage. These patients are typically managed with reconstruction of the ACL at the time of a high tibial osteotomy. The meniscal transplantation is performed simultaneously with these procedures only in rare situations, such as in very young patients. More commonly, meniscal allograft reconstruction is performed in a delayed fashion in a patient who has persistent symptoms following recovery from the initial procedures.

Meniscal allograft transplantation and cartilage restoration procedures

When combining cartilage restoration with meniscal transplantation in the same compartment, it is important to plan the exact sequence of events in a detailed preoperative plan. It is typically easier and safer for chondral procedures to be performed after all steps of the meniscal transplant have been completed to avoid inadvertent damage to the periosteal patch or osteochondral graft during meniscal instrumentation or suture repair [92]. On the other hand, the anterior horn of the transplanted meniscus could be damaged by subsequent cartilage procedure on the ipsilateral femoral condyle. For example, implanting an osteochondral allograft and performing a meniscal transplant will require that the posterior horn anchor be established before preparing the articular cartilage defect and implanting the osteochondral allograft

Fig. 9. Osteochondral allograft and simultaneous meniscus allograft transplantation in the same compartment requires carefully sequenced steps to avoid damaging either allograft.

plug. The bone plug and anterior horn of the meniscal allograft are gently retracted out of harms way during implantation of the osteochondral graft and inserted in a blind tunnel at the anatomic site of the anterior horn after the osteochondral graft implantation is completed (Fig. 9).

Outcomes

The literature supports good to excellent results of roughly 85% following MAT, with a measurable decrease in pain and increase in activity level, provided there is proper patient selection. There is a greater risk for graft failure in irradiated grafts, uncorrected malalignment, osteoarthritic compartments, and absence of bone anchorage of the allograft [103]. There is not a clear correlation with graft shrinkage or decreased cellular viability and poorer outcomes. There is a trend toward better results in more recent series, which reflects a collective improvement in patient selection, graft processing, and surgical technique over the last 15 years.

There is not a clear correlation with the physical appearance of the graft and outcome. In 1989, Milachowski and colleagues [45] reported that of six fresh-frozen and 16 freeze-dried meniscus allografts, the fresh-frozen grafts had a more normal gross appearance than the freeze-dried grafts that demonstrated more shrinkage, but this did not correlate with poorer outcomes. In 1999, Carter's [84] second-look arthroscopy of 38 cases at 2 years demonstrated four that had visible shrinkage of the graft and two that had progression of arthritis. These patients had inferior results. In contrast, Stollsteimer and colleagues [88] reported substantial pain relief in all 23 patients following cryopreserved allografts despite an average shrinkage of 37% found on MRI.

A decrease in cellularity and viability of the meniscus tissue has not correlated directly with poorer outcomes. In 1996, Wilcox and Goble [31] reported that 17 of 18 patients (94%) had a significant decrease in knee pain and improvement in function with universal patient satisfaction [71]. A second-look arthroscopy was performed on 13 patients (13 grafts) of which ten (71%) had a well-healed and functional meniscus. Biopsy performed on 8 of 14 grafts revealed an average of 80% viable meniscal tissue. A year earlier, van Arkel and de Boer [89] reported their prospective outcomes of 23 patients following cryopreserved meniscal transplant, of which 20 (87%) reported successful results, and peripheral healing was demonstrated in all but three of the patients examined with second-look arthroscopy. Histologic analysis demonstrated revascularization with viable meniscal chondrocytes. The three patients who failed had uncorrected malalignment. In 2001, Rath and colleagues [104] reported that 8 of 22 cryopreserved menisci (36%) tore after 2 years, necessitating six partial and two total meniscectomies and reimplantation, and the removed tissue revealed reduced cellularity compared with normal or torn native menisci. Fourteen patients reported a successful result, but there is no information regarding the cellularity of these more successful grafts.

Articular cartilage degeneration or a lack of allograft bone anchorage correlates with poor outcomes. In 1993, Garrett [72] reported that 35 of 43 (81%) patients were asymptomatic 2 years after complex procedures, with most failures occurring in knees that had grade IV chondromalacia. In 1994, Shelton and Dukes [105] reported that 15 of 16 patients who had less than grade II arthritic changes reported a significant decrease in pain and no recurrent effusion, whereas four patients who had transplantations into degenerative compartments had only slight improvement in symptoms. All second-look arthroscopies demonstrated complete peripheral healing, however, and although there was an average shrinkage of 15%, cellular viability was confirmed by biopsy. In 1995, Noyes and Barber-Westin [103] reported on 96 irradiated grafts, many of which were secured with bone at the posterior horn, but none had bone anchorage in the anterior and posterior horns. In this series, 29 menisci were removed by 2 years. Only 9% of the grafts healed, 31% were partially healed, and 58% failed clinically, with higher rates of failure in knees with arthrosis ($P < .001$) at a rate of 50% failure in knees with grade IV arthrosis. In 2001, Rodeo and colleagues [106,107] reported successful results in 22 of 33 (67%) patients. Of these, 14 of the 16 (88%) transplants that were anchored to bone at the anterior and posterior horns had good results, whereas only 8 of the 17 (47%) nonbone anchorage transplants were successful. In contrast to these studies, however, Cameron and Saha [83] reported good to excellent results in 87% of 67 irradiated allografts without bone anchors, many in patients who had advanced unicompartmental arthritis.

Several series have demonstrated the benefit of combining procedures to treat comorbid conditions that would otherwise be contraindications to MAT. Ligament reconstruction and cartilage restoration procedures can optimize the mechanical environment for the meniscal allograft. MAT can, in turn, provide protection for ligament reconstruction or cartilage restoration procedures. Zukor and colleagues [42] combined fresh meniscal and osteochondral allografts for knee injuries resulting in focal chondral defects and a deficient meniscus. At 1 year, 26 of 33 patients (79%) were clinically successful, with no meniscal failures. In the series by Veltri and colleagues [74] of 16 deep frozen or cryopreserved meniscal transplantations, 11 of which underwent either ACL or PCL reconstruction at surgery, 85% were asymptomatic. Sekiya and colleagues [108] reported retrospectively that 24 of 28 (86%) patients who had undergone ACL reconstruction with meniscal transplantation had normal or nearly normal IKDC scores, and nearly 90% had a normal or nearly normal Lachman and pivot shift exam, with an average maximum manual KT arthrometer side-to-side difference of 1.5 mm. Joint-space narrowing of the transplanted compartments was not significantly different from that of the contralateral knee. From these results the investigators concluded that restoration of meniscal function combined with ACL reconstruction may provide protection for the articular cartilage and improve joint stability, thereby eliminating a contraindication for meniscal transplantation. Yoldas and colleagues [102] reported on 31 patients following meniscus transplantation with and without combined ACL reconstruction. In this group, 20 patients received meniscal transplantation and ACL reconstruction and 11 patients who had stable ligaments underwent meniscal transplantation alone. Both groups had MAT with bone plugs medially and a bone bridge laterally. There were no significant differences in knee scores or joint-space narrowing on flexion weight-bearing views based on medial or lateral meniscus, concurrent ACL reconstruction, or the degree of chondrosis at arthroscopy. KT-1000 arthrometry revealed an average side-to-side difference of 2 mm (range, 2–7 mm). MAT with ligament reconstruction or cartilage restoration can provide relief of symptoms and restore high levels of function.

Discussion

Meniscus deficiency is considered by some authors to be a greatly underestimated problem in orthopedics today [103]. To patients, meniscal deficiency is a problem leading to pain, swelling, arthritic changes, and limitation of activity. To physicians, meniscal deficiency is a problem because of the lack of suitable solutions for their patients. To society, the sequelae of a meniscus-deficient knee translate into a loss of productivity and an increase in monetary expenditures for health care benefits. Many patient- and surgeon-specific variables, such as the degree of arthrosis, method of graft processing, surgical technique, types of concomitant procedures, and method of evaluation, differ among studies. Thus, it is difficult to make comparisons or draw conclusions on the basis of the existing literature.

The average age of the patient who is affected by knee ligament instability is 21 years. The average age of the patient who undergoes a total knee arthroplasty is 70 years. The average age for MAT is 33 years [109]. Knee instability primarily disables young athletes. Knees requiring salvage procedures, such as total knee arthroplasties, primarily affect individuals who are retirement-age, whereas patients who have meniscal-deficient knees represent a greater percentage of individuals within the day-to-day work force and who have major responsibilities in their personal lives. It should, therefore, be medically understandable that even a documented short-term improvement in an otherwise disabled population could be defined as a success.

Obtaining secure bone anchorage of the anterior and posterior horns, although technically more demanding, is necessary to maximize the potential for a successful outcome. The series by Rodeo [106], in which overall there were only 22 (66%) of 33 successful outcomes, demonstrated a much higher rate, with 14 (88%) successful outcomes of the 16 patients who had obtained bone anchorage compared with only 8 (47%) of the 17 patients who did not obtain bone anchorage. These clinical results coincide with the biomechanical understanding of the potential for benefit of a meniscal allograft [18,21,32].

The degree of arthrosis at the time of allograft transplantation is possibly the most important factor predicting outcome, with advanced arthrosis associated with the highest failure rates [89,103,110]. Using MRI, Rodeo [106] demonstrated that knees with advanced arthrosis had a greater propensity for graft extrusion, a finding believed to be associated with an increased risk for failure. Correcting limb malalignment is another factor believed to be critical for success [83]. van Arkel and de Boer [89] attributed their three graft failures to uncorrected limb alignment. Cameron and Saha [83] performed osteotomy in 34 of 63 patients. By realigning the knees to "unload" the involved compartment, they achieved a success rate comparable with that in the group as a whole, with a good or excellent result in 85% or 87%, respectively.

Meniscal shrinkage rating is inaccurate. At second-look arthroscopy in 22 cases, Carter [84] believed only three showed size reduction. Milachowski and colleagues [45] noted shrinkage of 33% to 66% in 14 of 23 menisci examined by second-look arthroscopy. It is not known if shrinkage occurs because of a subclinical immune response with graft-remodeling during cellular repopulation, a poor quality graft, excessive graft-loading during healing, the surgical technique, knee arthrosis, or some variable not currently recognized. The study by Stollsteimer and colleagues [88] suggests a low correlation between graft shrinkage and symptoms, however. MRI scans have demonstrated that the grafts can look similar to a normal meniscus, whereas others have shown signals consistent with degenerative changes [84,88,103,107]. Second-look arthroscopy is often necessary to define the exact quality of graft-healing [111–114].

Whether meniscal grafts prevent the progression of arthritis is unknown. Rath and colleagues [104] reported that the compartment space of the involved knees of 11 patients averaged 5.2 mm before surgery and 4.5 mm 2 years after transplantation. Carter [84] reported 2 of 46 knees with radiographic progression at almost 3 years. Rabbit studies demonstrate equal rates of radiographic degenerative changes at 1 year in meniscectomized and transplanted animals [115].

With respect to combined procedures, uncorrected comorbidities are contraindications to meniscal transplantation, but the beneficial effect of combined procedures is emerging and the synergy of concomitant reconstructions is evident. When a cartilage restoration or ligament reconstruction protects a meniscal transplant, a mutually beneficial relationship exists between the healthy functioning meniscus transplant and the ligament reconstruction or cartilage resurfacing procedures.

Summary

Despite encouraging intermediate-term benefits, the true long-term function of the transplanted meniscus remains unknown. The transplant appears to remodel and experience changes in its collagen fiber architecture that affect its load-sharing capabilities and long-term survival. The meniscal transplant surgeon should advise patients that this procedure is indicated for patients who have few other options, and the procedure is likely not curative in the long-term. However, establishing a pain-free and mechanically stable environment for even an intermediate period of time (ie, 5 or 10 years), as supported by the literature, seems entirely justified given the lack of alternatives and the added benefit of placing a patient chronologically at an age more appropriate for arthroplasty should it become necessary.

References

[1] Mow VC, Ratcliff A, Chern KY, et al. Structure and function relationships of the meniscus and knee. In: Mow VC, Arnoczky SP, Jackson DW, editors. Knee meniscus: basic and clinical foundations. New York: Raven Press; 1992. p. 37.

[2] Elliott DM, Guilak F, Vail TP, et al. Tensile properties of articular cartilage are altered by meniscectomy in a canine model of osteoarthritis. J Orthop Res 1999; 17(4):503–8.

[3] MacConaill MA. The movements of bones and joints; the mechanical structure of articulating cartilage. J Bone Joint Surg Br 1951;33B(2):251–7.

[4] Fu FH, Thompson WO. Motion of the meniscus during knee flexion. In: Mow VC, Arnoczky SP, Jackson DW, editors. Knee meniscus: basic and clinical foundations. New York: Raven Press; 1992. p. 75.

[5] Levy IM, Torzilli PA, Warren RF. The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg Am 1982;64(6): 883–8.

[6] Shoemaker SC, Markolf KL. The role of the meniscus in the anterior-posterior stability of the loaded anterior cruciate-deficient knee. Effects of partial versus total excision. J Bone Joint Surg Am 1986;68(1): 71–9.

[7] Levy IM, Torzilli PA, Fisch ID. The contribution of the menisci to the stability of the knee. In: Mow VC, Arnoczky SP, Jackson DW, editors. Knee meniscus: basic and clinical foundations. New York: Raven Press; 1992. p. 107–15.

[8] Thompson WO, Thaette FL, Fu FH, et al. Tibial meniscal dynamics using three-dimensional reconstruction of magnetic resonance images. Am J Sports Med 1991;19:210–5.

[9] Jager A, Welsch F, Braune C, et al. Ten year follow-up after single incision anterior cruciate ligament reconstruction using patellar tendon autograft. Z Orthop Ihre Grenzgeb 2003;141(1):42–7.

[10] Shelbourne KD, Gray T. Results of anterior cruciate ligament reconstruction based on meniscus and

articular cartilage status at the time of surgery. Five- to fifteen-year evaluations. Am J Sports Med 2000; 28(4):446–52.

[11] Weismeier K, Worth CJ, Milachowski KA. [Transplantation of the meniscus. Experimental study.] Rev Chir Orthop Reparatrice Appar Mot 1988;74:155–9 [in French].

[12] Hsu RWW, Himeno S, Coventry MB. Transactions of the 34th Annual Meeting of the Orthopedic Research Society, vol. 13. Park Ridge (IL): Orthopedic Research Society; 1988.

[13] Rohrie H, Scholten R. Joint forces in the human pelvis-leg skeleton during walking. J Biomech 1984; 17(6):409–24.

[14] Ahmed AM. The load bearing of the knee meniscus. In: Mow VC, Arnoczky SP, Jackson DW, editors. Knee meniscus: basic and clinical foundations. New York: Raven Press; 1992. p. 59–73.

[15] Ahmed AM, Burke DL. In-vitro measurement of static pressure distribution in synovial joints–Part I: tibial surface of the knee. J Biomech Eng 1983; 105(3):216–25.

[16] Walker BF, Erkman MJ. The role of the menisci in force transmission across the knee. Clin Orthop 1975;(109):184–92.

[17] Baratz ME, Fu FH, Mengato R. Meniscal tears: the effect of meniscectomy and of repair on intraarticular contact areas and stress in the human knee. A preliminary report. Am J Sports Med 1986;14(4): 270–5.

[18] Paletta Jr GA, Manning T, Snell E, et al. The effect of allograft meniscal replacement on intraarticular contact area and pressures in the human knee. A biomechanical study. Am J Sports Med 1997;25(5): 692–8.

[19] Seedhom BB, Hargreaves DJ. Transmission of load in the knee joint with special reference to the role of the menisci, part II: experimental results, discussions, and conclusions. Eng Med 1979;8: 220–8.

[20] Alhalki MM, Howell SM, Hull ML. How three methods for fixing a medial meniscal autograft affect tibial contact mechanics. Am J Sports Med 1999;27: 320–8.

[21] Chen MI, Branch TP, Hutton WC. Is it important to secure the horns during lateral meniscal transplantation? A cadaveric study. Arthroscopy 1996;12(2): 174–81.

[22] DeHaven KE. [Meniscus resection versus reattachment of the meniscus.] Orthopade 1994;23:133–6 [in German].

[23] Szomor ZL, Martin TE, Bonar F, et al. The protective effects of meniscal transplantation on cartilage. An experimental study in sheep. J Bone Joint Surg Am 2000;82(1):80–8.

[24] Arnoczky SP, McDevitt CA. The meniscus: structure function, repair and replacement. In: Buckwalter JA, Einhorn TA, Simon SR, editors. Orthopedic basic Science: biology and biomechanics of the musculoskeletal system. Rosemont (IL): American Academy of Orthopedic Surgeons; 2000. p. 531–45.

[25] Mow VC, Holmes MH, Lai WM. Fluid transport and mechanical properties of articular cartilage: a review. J Biomech 1984;17(5):377–94.

[26] Favenesi JA, Shaffer JC, Mow VC. Biphasic mechanical properties of knee meniscus. Trans Orthop Res Soc 1983;8:57.

[27] Fithian DC, Kelly MA, Mow VC. Material properties and structure-function relationships in the menisci. Clin Orthop Relat Res 1990;Mar(252):19–31.

[28] Skaggs DL, Warden WH, Mow VC. Radial tie fibers influence the tensile properties of the bovine medial meniscus. J Orthop Res 1994;12:176.

[29] Lee SJ, Aadalen KJ, Lorenz EP, et al. Tibiofemoral contact mechanics following serial medial meniscectomies in the human cadaveric knee. AOSSM Annual Meeting, Quebec City, June 24–27, 2004.

[30] Fairbank TJ. Knee joint changes after meniscectomy. J Bone Joint Surg Br 1948;30:664–70.

[31] Wilcox TR, Goble EM. Goble technique of meniscus transplantation. Am J Knee Surg 1996;9:1.

[32] Alhalki MM, Hull ML, Howell SM. Contact mechanics of the medial tibial plateau after implantation of a medial meniscal allograft. A human cadaveric study. Am J Sports Med 2000;28(3):370–6.

[33] Huckle JR. Is meniscectomy a benign procedure? A long-term follow-up study. Can J Surg 1965;8:254.

[34] Johnson RJ, Kettlekamp DB, Clark W, et al. Factors affecting late results after meniscectomy. J Bone Joint Surg Am 1974;56:719.

[35] Lynch MA, Henning CE. Osteoarthritis in the ACL deficient knee. In: Feagin Jr JA, editor. The cruciate ligaments. New York: Churchill, Livingstone; 1988. p. 385.

[36] Lynch MA, Henning CE, Glick KR. Knee joint surface changes: Long-term follow-up meniscus tear treatment and stable anterior cruciate ligament reconstruction. Clin Orthop 1983;172:148.

[37] O'Brien WR. Degenerative arthritis of the knee following anterior cruciate ligament injury: Role of the meniscus. Sports Med Arthroscopy Rev 1993; 1:114.

[38] Tapper EM, Hoover NW. Late results after meniscectomy. J Bone Joint Surg Am 1969;51(3):517–26.

[39] Levy IM, Torzilli PA, Gould JD, et al. The effect of lateral meniscectomy on motion of the knee. J Bone Joint Surg Am 1989;71(3):401–6.

[40] Lexer E. Substitution of whole or half Joints from freshly amputated extremities by free plastic operation. Surg Gynecol Obstet 1908;6:601–7.

[41] Lexer E. Joint transplantations and arthroplasty. Surg Gynecol Obstet 1925;40:782–809.

[42] Zukor DJ, Cameron JC, Brooks PJ, et al. The fate of human meniscal allografts. In: Ewing JW, editor. Articular cartilage and knee joint function: basic science and arthroscopy. New York: Raven Press; 1990. p. 147.

[43] Brown KL, Cruess RL. Bone and cartilage trans-

plantation in orthopedic surgery review. J Bone Joint Surg Am 1982;64:270.

[44] Cummins JF, Mansour JN, Howe Z, et al. Meniscal transplantation and degenerative articular change: An experimental study in the rabbit. Arthroscopy 1997; 13:485.

[45] Milachowski KA, Weismeier K, Worth CJ, et al. Homologous meniscus transplantation: Experimental and clinical results. Int Orthop 1989;13:1–11.

[46] Milachowski KA, Kohn D, Wirth CJ. Transplantation of allogenic menisci. Orthopade 1994; 23:160.

[47] Arnoczky SB, O'Brian S, DeCarlo E, et al. Cell survival after transplantation of fresh meniscal allograft: DNA probe analysis in goat model. Am J Sports Med 1988;21:540.

[48] Jackson DW, Whelan J, Simon TM. Cell survival of the transplantation of fresh meniscal allograft: DNA probe analysis in a goat model. Am J Sports Med 1993;21:540–50.

[49] Mikic ZD, Brankoy MZ, Tubic MV, et al. Allograft meniscal transplantation in a dog. Acta Orthop Scand 1993;64:329.

[50] Arnoczky SP, McDevitt CA. Meniscal replacement using cryopreserved allograft: Experimental study in the dog. Clin Orthop 1990;252:121.

[51] Arnoczky SP, Milachowski KA. Meniscal allografts: where do we stand? In: Ewing JW, editor. Articular cartilage and the knee joint function: basic science and arthroscopy. New York: Raven Press; 1990. p. 129.

[52] Jackson DW, McDevitt CA, Simon TM, et al. Meniscal transplantation using fresh and cryo-preserved allograft: An experimental study in goats. Am J Sports Med 1992;20:646.

[53] Friedlaender GE, Strong DM, Sell KW. Studies on the antigenicity of bone. I. Freeze-dried and deep-frozen bone allografts in rabbits. J Bone Joint Surg Am 1976;58:854–8.

[54] Fabbriciani C, Lucania L. Meniscal allografts: Cryopreservation vs. deep frozen technique. An experimental study in goats. Knee Surg Sports Traumatol Arthrosc 1997;5:124.

[55] Ochi M, Ishida O, Daisaku H, et al. Immune response to fresh meniscal allografts in mice. J Surg Res 1995; 58(5):478–84.

[56] Goble EM, Kohn D, Verdonk R, et al. Meniscal substitutes—human experience. Scand J Med Sci Sports 1999;9:146–57.

[57] Friedlaender GE, Strong DM, Sell KW. Studies on the antigenicity of bone. II. Donor-specific anti-HLA antibodies in human recipients of freeze-dried allografts. J Bone Joint Surg Am 1984;66(1):107–12.

[58] Moseley TA, Haudenschild DR, Rose L, et al. Interleukin-17 family and IL-17 receptors. Cytokine Growth Factor Rev 2003;14(2):155–74.

[59] Hamlet W, Liu SH, Yang R. Destruction of a cyropreserved meniscal allograft: a case for acute rejection. Arthroscopy 1997;13(4):517–21.

[60] De Boer HH, Koudstaal J. The fate of meniscus cartilage after transplantation of cryopreserved nontissue-antigen-matched allograft. A case report. Clin Orthop 1991;(266):145–51.

[61] van Arkel ER, van den Berg-Loonen EM, van Wersch JW, et al. Human leukocyte antigen sensitization after cryopreserved human meniscal transplantations. Transplantation 1997;64:531–3.

[62] Khoury MA, Goldberg VM, Stevenson S. Demonstration of HLA and ABH antigens in fresh and frozen human menisci by immunohistochemistry. J Orthop Res 1994;12(6):751–7.

[63] Standards for tissue banking. Mclean (VA): American Association of Tissue Banks; 2002.

[64] Nemzek JA, Arnoczky SP, Swenson CL. Retroviral transmission by the transplantation of connective-tissue allografts. An experimental study. J Bone Joint Surg Am 1994;76:1036–41.

[65] Buck BE, Resnick L, Shah SM, et al. Human immunodeficiency virus cultured from bone. Implications for transplantation. Clin Orthop 1990;251:249–53.

[66] Verdonk R, Van Daele P, Claus B, et al. Viable meniscus transplantation. Orthopade 1994;23: 153–9 [German].

[67] Arnoczky SP, McDevitt CA, Schmidt MB, et al. The effect of cryopreservation on canine menisci: a biochemical, morphologic, and biomechanical evaluation. J Orthop Res 1988;6:1–12.

[68] Yahia LH, Drouin G, Zukor D. The irradiation effect on the initial mechanical properties of meniscal grafts. Biomed Mater Eng 1993;3:211–21.

[69] Fabbriciani C, Lucania L, Milano G, et al. Meniscal allografts: cryopreservation vs deep-frozen technique. An experimental study in goats. Knee Surg Sports Traumatol Arthrosc 1997;5:124–34.

[70] Jackson DW, Windler GE, Simon TM. Intraarticular reaction associated with the use of freezedried, ethylene oxide-sterilized bone-patella tendon-bone allografts in the reconstruction of the anterior cruciate ligament. Am J Sports Med 1990;18:1–10.

[71] Outerbridge RE. The etiology of chondromalacia patellae. J Bone Joint Surg Br 1961;43:752–7.

[72] Garrett JC. Meniscal transplantation: review of forty-three cases with two-to-seven year follow up. Sports Med Arthroscopy Rev 1993;1:164–7.

[73] Siegel MG, Roberts CS. Meniscal allografts. Clin Sports Med 1993;12:59.

[74] Veltri DM, Warren RF, Wickiewicz TL, et al. Current status of allograft meniscal transplantation. Clin Orthop 1994;303:44.

[75] Rosenberg TD, Paulos LE, Parker RD, et al. The forty-five-degree posteroanterior flexion weight-bearing radiograph of the knee. J Bone Joint Surg Am 1988; 70:1479–83.

[76] Potter HG, Linklater JM, Allen AA, et al. Magnetic resonance imaging of articular cartilage in the knee. An evaluation with use of fast-spin-echo imaging. J Bone Joint Surg Am 1998;80:1276–84.

[77] Kohn D, Moreno B. Meniscus insertion anatomy

as a basis for meniscus replacement: a morphological cadaveric study. Arthroscopy 1995;11:96–103.

[78] Kennedy S, Shaffer B, Yao L. Preoperative planning in meniscal allograft reconstruction. Presented at the 24th annual meeting of the American Orthopedic Society for Sports Medicine. Orlando, FL, July 12, 1998.

[79] Carpenter JE, Wojtys EM, Huston LJ. Pre-operative sizing of meniscal replacements. Presented at the 12th annual meeting of the Arthroscopy Association of North America. Palm Desert, CA, April 1, 1993.

[80] Pollard ME, Kung Q, Berg EE. Radiographic sizing for meniscal transplantation. Arthroscopy 1995;11: 684–7.

[81] Shaffer B, Kennedy S, Klimkiewicz J, et al. Preoperative sizing of meniscal allografts in meniscus transplantation. Am J Sports Med 2000;28:524–33.

[82] Verdonk R, Kohn D. Harvest and conservation of meniscal allografts. Scand J Med Sci Sports 1999;9: 158–9.

[83] Cameron JC, Saha S. Meniscal allograft transplantation for unicompartmental arthritis of the knee. Clin Orthop 1997;337:164–71.

[84] Carter TR. Meniscal Allograft Transplantation. Sports Med Arthroscopy Rev 1999;7:51–62.

[85] Cole BJ, Fox JA, Lee SJ, et al. Bone bridge in slot technique for meniscal transplantation. Op Tech Sports Med 2003;11:144–55.

[86] Farr J, Meneghini RM, Cole BJ. Allograft interference screw fixation in meniscus transplantation. Arthroscopy 2004;20:322–7.

[87] Fox JA, Lee SJ, Cole BJ. Bone plug technique for meniscal transplantation. Op Tech Sports Med 2003;11:161–9.

[88] Stollsteimer GT, Shelton WR, Dukes A, et al. Meniscal allograft transplantation: a 1- to 5-year follow-up of 22 patients. Arthroscopy 2000;16:343–7.

[89] van Arkel ER, de Boer HH. Human meniscal transplantation. Preliminary results at 2 to 5-year follow-up. J Bone Joint Surg Br 1995;77(4):589–95.

[90] Johnson DL, Swenson TM, Livesay GA, et al. Insertion-site anatomy of the human menisci: gross, arthroscopic, and topographical anatomy as a basis for meniscal transplantation. Arthroscopy 1995;11: 386–94.

[91] Berlet GC, Fowler PJ. The anterior horn of the medial meniscus. An anatomic study of its insertion. Am J Sports Med 1998;26:540–3.

[92] Albrecht-Olsen P, Lind T, Kristensen G, et al. Failure strength of a new meniscus arrow repair technique: biomechanical comparison with horizontal suture. Arthroscopy 1997;13:183–7.

[93] Albrecht-Olsen P, Lind T, Kristensen G, et al. Failure strength of a new meniscus arrow repair technique: biomechanical comparison with horizontal suture. Arthroscopy 1997;13:183–7.

[94] Boenisch UW, Faber KJ, Ciarelli M, et al. Pull-out strength and stiffness of meniscal repair using absorbable arrows or Ti-Cron vertical and horizontal loop sutures. Am J Sports Med 1999;27: 626–31.

[95] Ghazavi MT, Pritzker KP, Davis AM, et al. Fresh osteochondral allografts for post-traumatic osteochondral defects of the knee. J Bone Joint Surg [Br] 1997;79(6):1008–13.

[96] Lobenhoffer P, Agneskirchner JD. Improvements in surgical technique of valgus high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 2003;11(3): 132–8.

[97] Gugenheim Jr JJ, Brinker MR. Bone realignment with use of temporary external fixation for distal femoral valgus and varus deformities. J Bone Joint Surg Am 2003;85-A(7):1229–37.

[98] Papageorgiou CD, Gil JE, Kanamori A, et al. The biomechanical interdependence between the anterior cruciate ligament replacement graft and the medial meniscus. Am J Sports Med 2001;29(2): 226–31.

[99] Barrack RL, Bruckner JD, Kneisl J, et al. Outcome of nonoperatively treated complete tears of the anterior cruciate ligament in active young adults. Clin Orthop Relat Res 1990;Oct(259):192–9.

[100] Bonamo JJ, Fay C, Firestone T. The conservative treatment of the anterior cruciate deficient knee. Am J Sports Med 1990;18(6):618–23.

[101] Cole BJ, Carter TR, Rodeo SA. Allograft meniscal transplantation: background, techniques, and results. Instr Course Lect 2003;52:383–96.

[102] Yoldas EA, Sekiya JK, Irrgang JJ, et al. Arthroscopically assisted meniscal allograft transplantation with and without combined anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2003;11(3):173–82.

[103] Noyes FR, Barber-Westin SD. Irradiated meniscal allografts in the human knee: a two-to-five year follow-up study. Orthop Trans 1995;19:417.

[104] Rath E, Richmond JC, Yassir W, et al. Meniscal allograft transplantation. Two- to eight-year results. Am J Sports Med 2001;29(4):410–4.

[105] Shelton WR, Dukes AD. Meniscus replacement with bone anchors: a surgical technique. Arthroscopy 1994;10(3):324–7.

[106] Rodeo SA. Meniscal allografts–where do we stand? Am J Sports Med 2001;29(2):246–61.

[107] Rodeo SA, Seneviratne A, Suzuki K, et al. Histological analysis of human meniscal allografts. A preliminary report. J Bone Joint Surg Am 2000;82: 1071–82.

[108] Sekiya JK, Giffin JR, Irrgang JJ, et al. Clinical outcomes after combined meniscal allograft transplantation and anterior cruciate ligament reconstruction. Am J Sports Med 2003;31(6):896–906.

[109] Cole BJ, Rodeo S, Carter T. Allograft meniscus transplantation: indications, techniques, and results. J Bone Joint Surg Am 2002;84A:1236–50.

[110] Garrett JC, Stevenson RN. Meniscal transplantation in the human knee: a preliminary report. Arthroscopy 1991;7:57.

[111] Farley TE, Howell SM, Love KF, et al. Meniscal tear: MR and arthrographic findings after arthroscopic repair. Radiology 1991;180:517–22.

[112] Patten RM, Rolfe BA. MRI of meniscal allografts. J Comput Assist Tomogr 1995;19:243–6.

[113] Potter HG, Rodeo SA, Wickiewicz TL, et al. MR imaging of meniscal allografts: correlation with clinical and arthroscopic outcomes. Radiology 1996; 198:509–14.

[114] Verdonk R. Alternative treatments for meniscal injuries. J Bone Joint Surg Br 1997;79:866–73.

[115] Rijk PC, de Rooy TP, Coerkamp EG, et al. Radiographic evaluation of the knee joint after meniscal allograft transplantation. An experimental study in rabbits. Knee Surg Sports Traumatol Arthrosc 2002; 10(4):241–6.