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ALLOGRAFT MENISCAL TRANSPLANTATION

BACKGROUND, TECHNIQUES, AND RESULTS

BY BRIAN J. COLE, MD, THOMAS R. CARTER, MD, AND SCOTT A. RODEO, MD

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The treatment of meniscal injuries has evolved over the last thirty years. Initially, the importance of the meniscus was poorly understood, and meniscal excision was routinely performed as the primary treatment for meniscal injury[1]. However, contemporary understanding of the natural history and biomechanical consequences of a meniscectomized knee has led to a commitment to meniscal preservation[2]. Still, there is an existing population of patients who have undergone subtotal meniscectomy, and there continue to be instances in which meniscal preservation is not possible. In these cases, knee function is adversely affected, with disruption of important meniscal functions including load-sharing, shock absorption, joint stability, joint nutrition, and overall protection of the articular cartilage. In an effort to restore normal knee anatomy and biomechanics, meniscal allografts are used to replace the native meniscus in selected symptomatic individuals. Intermediate-term reports indicate that excellent pain relief and improved function can be achieved when rigid indications are adhered to, and it is hoped that emerging long-term data will demonstrate a continued improvement compared with the meniscus-deficient knee[3-5].

Macroscopic Anatomy and Implications for Meniscal Transplantation

The menisci are semilunar-shaped fibrocartilage structures with unique gross and histological anatomy. Circumferentially oriented collagen fibers provide resistance to hoop stresses. Radially oriented "ties" hold circumferential fibers together and provide resistance to shear. The success of meniscal transplantation, including its ability to transmit load across the tibiofemoral joint, is presumed to depend on careful size and shape-matching of the transplanted meniscus to the native meniscus. The tolerance of the tibiofemoral compartment to meniscal size mismatch is unknown.

The anterior and posterior horns directly attach to bone by means of interdigitating collagen fibers oriented to optimally transmit load and shear from the meniscus to the tibia[6]. The horn insertions contain type-I and II nerve endings postulated to have mechanoreceptive and proprioceptive functions[7]. It is unknown if functional reinnervation occurs in a transplanted meniscus.

The medial meniscus is firmly attached to the deep medial collateral ligament and coronary ligament and is less mobile than the lateral meniscus[8]. Other than its attachment to the menis-cofemoral ligaments (Humphrey and Wrisberg ligaments), which run from the inner aspect of the medial femoral condyle to the posterior horn of the lateral meniscus, the lateral meniscus is less firmly attached to the capsule. It is stabilized principally at the popliteus hiatus by popliteomeniscal fasciculi (posterosuperiorly and anteroinferiorly)[9,10]. The popliteomeniscal fasciculi and the meniscofemoral ligaments are not restored with lateral meniscal transplantation. The biomechanical consequences of this, if any, are not known.

Microscopic Anatomy and Biochemical Composition

Meniscal cells are either elongated (the cells on the surface) or ovoid (those situated deeper) with limited mitochondria, suggesting anaerobic metabolism[11]. The extracellular matrix contains water (74% of the total weight), collagen (type I makes up 55% to 65% of the dry weight), and glycosaminoglycans (1% to 2% of the dry weight). This composition allows the meniscus to behave as a fiber-reinforced solid material providing resistance to tension, compression, and shear. Other collagens (types II, III, V, and VI) make up 5% to 10% of the dry weight. Noncollagenous proteins, including elastin, fibronectin, and thrombospondin, probably aid in matrix organization by

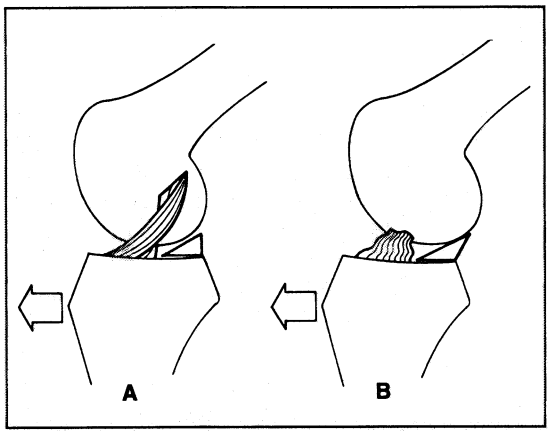


Fig. 1

The medial meniscus acts as a restraint to anterior tibial translation in the anterior cruciate ligament-deficient knee. (Reprinted from: Levy IM, Torzilli PA, Warren RF. The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg Am. 1982;64:887.)

binding other molecules. The vascularity of the meniscus originates from the superior and inferior medial and lateral geniculate arteries, forming a perimeniscal capillary plexus penetrating 10% to 30% of the width of the medial meniscus and 10% to 25% of the width of the lateral meniscus[11]. A peripheral vascular synovial fringe extends 1 to 3 mm over the femoral and tibial surfaces of the meniscus and participates in the healing response.

Material Properties and Function

The meniscus behaves as a fiber-reinforced, porous-permeable composite material containing a solid phase (matrix proteins) and a fluid phase (water)[12,13]. The principal function of the meniscus is to transmit load across the tibiofemoral joint, improve joint congruency, and increase the surface area of joint contact. During loading, the meniscus experiences tensile, compressive, and shear stress. Joint-loading results in radially oriented forces that lead to tensile stress ("hoop stress") in the circumferential collagen fibers. The medial meniscus transmits 50% of the joint load in the medial compartment, and the lateral meniscus transmits 70% of the joint load in the lateral compartment. The menisci transmit 50% of the joint load when the knee is in extension and 85% to 90% of the joint load when the knee is in flexion[14]. An in vitro study demonstrated that removal of 16% to 34% of the meniscus resulted in a 350% increase in contact forces[15]. In vitro studies also demonstrated that meniscal transplantation improves contact area and contact pressures compared with those following total meniscectomy but secure fixation of both the anterior and the posterior horn is required[16-18].

The meniscus experiences high compressive forces, which are resisted by the swelling pressure provided by proteoglycans and water. Water flows through the porous-permeable solid matrix during compressive loading, contributing to meniscal shock absorption, aiding in joint lubrication, and providing nutrition to the articular cartilage[13].

Unlike the lateral meniscus, the medial meniscus serves as a restraint to anterior tibial translation in the anterior cruciate ligament-deficient knee (Fig. 1)[19,20]. A recent cadaveric study demonstrated that the resultant force in an anterior cruciate ligament graft increased significantly ($p < 0.05$) following medial meniscectomy, a finding that supports the notion that medial meniscal transplantation is indicated at the time of reconstruction of the anterior cruciate ligament[21]. Also, a cadaveric biomechanical study demonstrated that knees with an absent anterior cruciate ligament and a deficient medial meniscus exhibited greater varus-valgus laxity than did those with an absent anterior cruciate ligament but an intact medial meniscus[22].

Natural History of the Meniscus-Deficient Knee

Numerous clinical studies have documented the progressive degenerative changes that occur in the meniscus-deficient knee. In general, the degree of degenerative change is directly proportional to the amount of meniscus that was removed[23,24], and the most important factor affecting outcome following meniscectomy is the degree of concomitant degenerative change[25-28]. Degenerative changes generally progress more rapidly in the lateral compartment following lateral meniscectomy[29,30]. Other factors contributing to degenerative change include knee stability (with inferior results when there is concomitant anterior cruciate ligament insufficiency[25,31]), type of tear (with the results associated with chronic degenerative tears inferior to those associated with acute tears[26]), and knee alignment (with better results following medial meniscectomy in a valgus knee[31]).

Fairbank[2] reported three radiographic findings (now commonly referred to as "Fairbank's changes") after meniscectomy: (1) formation of a ridge on the femoral condyle, (2) flattening of the femoral condyle, and (3) joint-narrowing. Tapper and Hoover[32], in a study in which 213 of 1005 patients who had undergone total meniscectomy were followed for ten to thirty years, found that 45% (seventy-seven) of the 172 male patients and only 10% (four) of the forty-one female patients were symptom-free, with resolution of symptoms independent of the age of the patient at the time of the meniscectomy or the duration of follow-up. Johnson et al.[29] reported on a study in which ninety-nine of 440 patients who had had a meniscectomy were followed for a mean of 17.5 years; at the time of follow-up, 74% (seventy-three) of the ninety-nine involved knees demonstrating at least one Fairbank change compared with 6% (six) of the contralateral knees. Frank degenerative joint disease was diagnosed in 40% (forty) of the involved knees compared with 6% (six) of the contralateral knees. The results following lateral meniscectomies were worse than those following medial meniscectomies. This finding of rapid deterioration in the lateral compartment following lateral meniscectomy was also documented by Yocum et. al.[30], who found that only 58% (fifteen) of twenty-six patients had a satisfactory

result at an average of thirty-five months after lateral meniscectomy.

More recent studies have involved patients who had had an arthroscopic partial meniscectomy, although very few reports have provided outcomes at more than ten years postoperatively[27,31]. In general, degenerative changes following partial meniscectomy progress less rapidly than do those after total meniscectomy[24]. For example, McGinty et al.[24] found early radiographic changes in 62% (fifty-five) of eighty-nine patients treated with total meniscectomy compared with 36% (fourteen) of thirty-nine treated with partial meniscectomy. Patients without signs of joint degeneration at the time of arthroscopic partial meniscectomy have a higher rate of success than do patients with signs of joint degeneration (90% compared with 60% to 70%)[26-28,33]. More recent studies have demonstrated deterioration over time. For example, Jaureguito et al.[34] reported that, at the time of an early follow-up, 92% (twenty-four) of their twenty-six patients had a successful result following partial lateral meniscectomy, but only 67% (sixteen) had a successful result at a mean of eight years. Similarly, Schimmer et al.[27] reported a successful result in 92% (109) of 119 patients at four years but in only 78% (ninety-three) of the 119 at twelve years. Notably, 95% (fifty-five) of fifty-eight patients without degenerative change at the time of the meniscectomy still had an excellent or good result at twelve years. A study in sheep suggested that meniscal allografts implanted following meniscectomy provide protection against damage to the articular cartilage comparable with that provided by autografts[35]. Additional reports have demonstrated that areas of articular cartilage covered by meniscal allografts have appreciably fewer arthritic changes, with associated reductions in contact pressures, than uncovered areas[36-38].

Graft Processing and Preservation

Stringent donor selection and screening beginning with the recording of a comprehensive medical and social history is a critical first step in ensuring procurement of disease-free allograft tissue. The American Association of Tissue Banks has defined the recommended testing protocol. Serological screening is performed for human immunodeficiency virus (HIV) p24 antigen, HIV-1/HIV-2 antibody, human T-cell lymphotropic virus-I (HTLV-I) and HTLV-II, hepatitis-B surface antigen, hepatitis-B core antibody, hepatitis-C antibody, and syphilis. Many tissue banks perform polymerase chain reaction testing, which can detect one HIV-infected cell out of 10^6 cells. The current "window" of time for development of detectable antibodies to HIV is approximately twenty to twenty-five days (in this time, a donor may be infected but test negative for HIV). Blood cultures for aerobic and anaerobic bacteria are done, and lymph node sampling may be performed.

Graft processing, including débridement, ultrasonic/pulsatile washing, and use of ethanol to denature proteins, further lowers the risk of disease transmission. Freezing lowers the risk even more, but HIV can survive washing, freezing, and freeze-drying[39]. It is evident that safety depends on donor screening and not graft processing. The current risk of HIV transmission by frozen connective-tissue allografts is estimated to be one in eight million[40].

The tissue is procured within twelve hours after death (fresh grafts) or within twenty-four hours after death if the body had been stored at 4°C. The tissue may be harvested with use of sterile surgical technique or it may be procured in a clean, nonsterile environment and secondarily sterilized with irradiation, ethylene oxide, or chemical

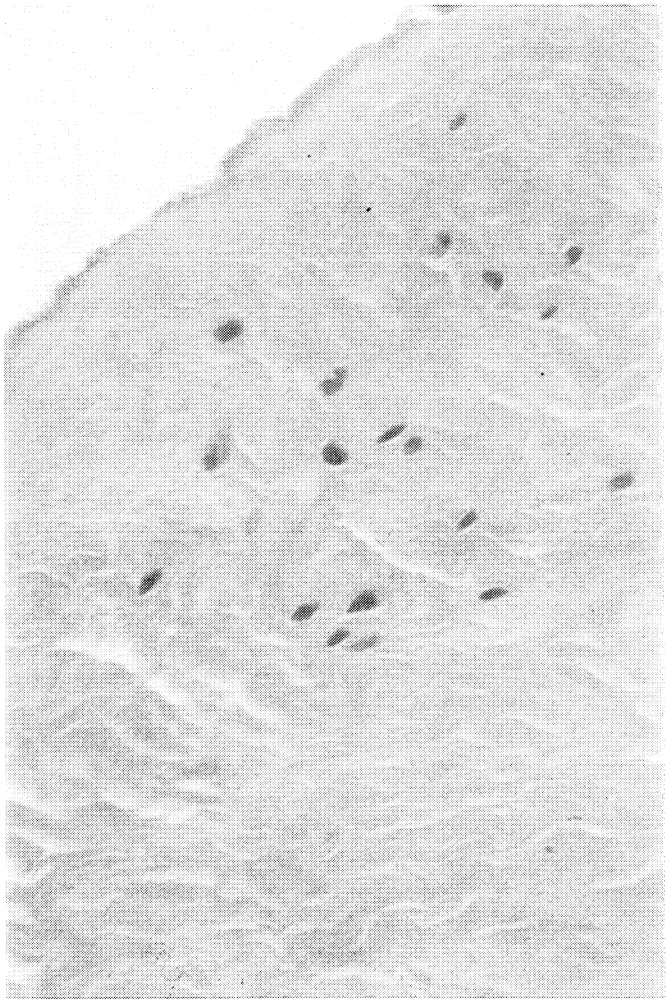


Fig. 2

A biopsy specimen from a deep-frozen human meniscal allograft, demonstrating incomplete cellular repopulation.

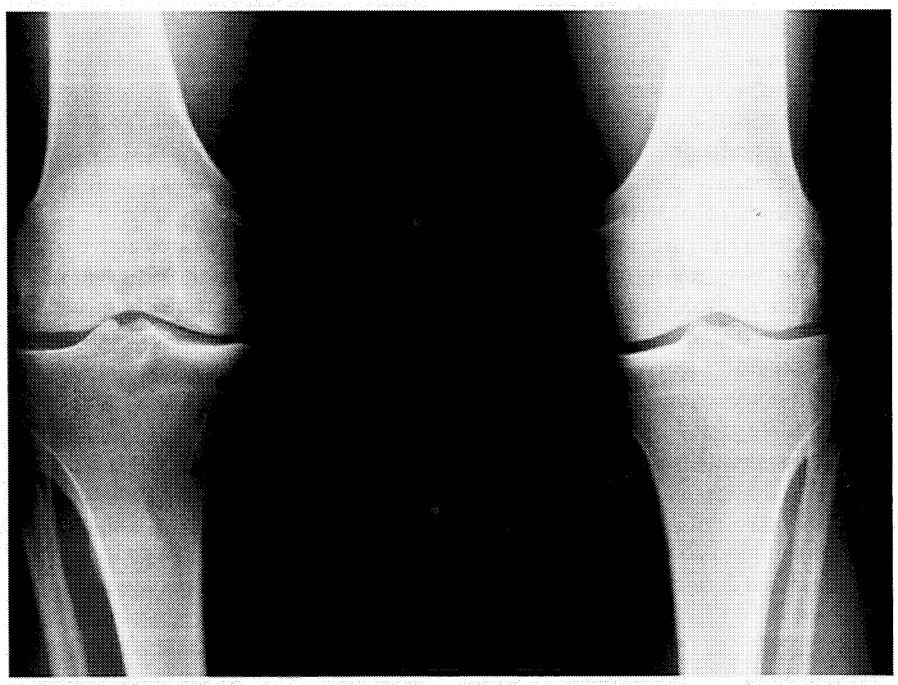


Fig. 3-A

Figs. 3-A and 3-B Radiographs of a thirty-two-year-old man with a history of medial meniscectomy of the right knee. **Fig. 3-A** An extension weight-bearing anteroposterior radiograph demonstrating an intact medial joint space.

means. Following harvest, 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 twelve hours after death. The tissue is stored in a culture medium at 4°C or 37°C in order to maintain viable cells. Transplantation must be done within several days of graft procurement, resulting in difficult logistics[41]. The proportion of cells that survive and the duration for which they survive after transplantation are unknown. Jackson et al.[36] used DNA probe analysis in a goat model and found that all of the donor cells in a fresh meniscal transplant were rapidly replaced by host cells.

Cryopreservation by controlled-rate freezing includes use of a cryoprotectant (such as dimethylsulfoxide) in an attempt to maintain cell viability while allowing prolonged storage without affecting graft biomechanics[42]. Fresh-frozen grafts are rapidly frozen to −80°C, killing cells without an important effect on graft material properties. Lyophilization, or freeze-drying, kills cells and may adversely affect graft material properties and result in graft shrinkage[43,44]. Unlike those of fresh osteochondral grafts, the morphological and biochemical characteristics of meniscal allografts do not seem to be improved by graft cell viability; thus, the most commonly implanted grafts are either fresh-frozen or cryopreserved. Experimental studies in goats have suggested that there are no important differences between cryopreserved and deep-frozen grafts[36,45].

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 gray]) may adversely affect the material properties of the meniscus[46]. Lower doses of gamma-irradiation (<2.0 Mrads [<20,000 gray]) may be used for bacterial sterilization. Ethylene oxide is used only for lyophilized grafts, but it is not recommended since the ethylene chlorohydrin byproduct has been found to induce synovitis[47]. Chemical steriliza-

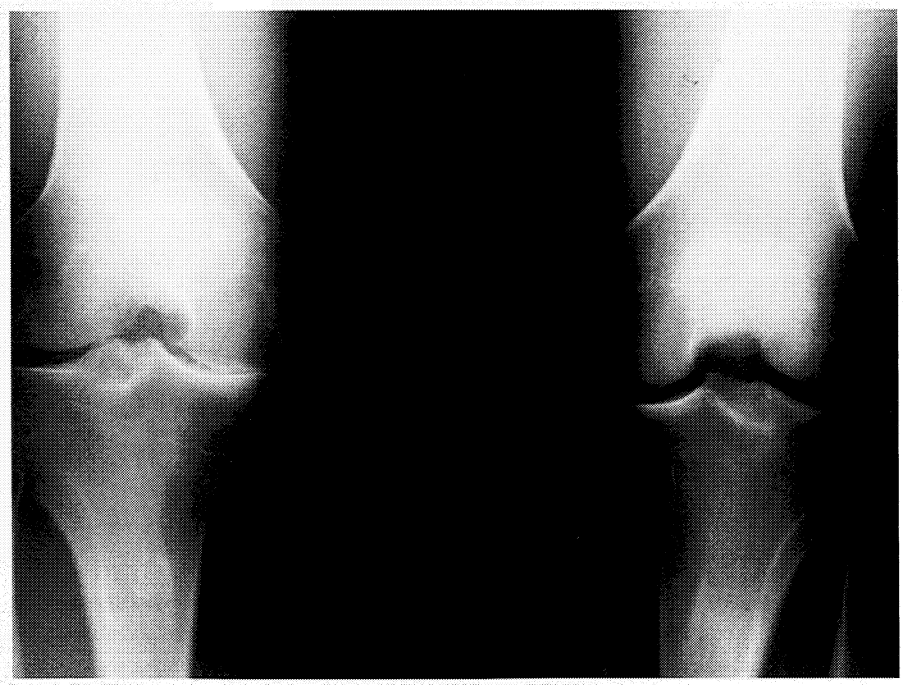


Fig. 3-B

A 45° flexion weight-bearing posteroanterior radiograph demonstrating complete loss of the joint space in the medial compartment. On the basis of this radiograph, the patient was excluded as a candidate for meniscal allograft transplantation.

tion may be done with use of proprietary bactericidal/virucidal solutions.

Immunological Concerns

Class-I and II histocompatibility antigens are expressed on the cells of a meniscal allograft, even after deep-freezing, indicating the potential for an immune response[48]. Attached bone plugs and synovial tissue also contain immunogenic cells, and it is well established that bone remains immunogenic even after freezing[49]. We are aware of only one report providing clinical and histological evidence of frank immunological rejection of a cryopreserved, non-tissue-antigen-matched meniscal allograft[50]. Although frank immunological rejection is rarely seen, there is histological evidence of an immune response directed against the graft. For example, one study demonstrated sensitization to HLA Class-I and Class-II antigens in recipients of cryopreserved, non-tissue-antigen-matched meniscal allografts; however, there was no clinical evidence of rejection in these patients[46]. Rodeo et al.[51] reported immunoreactive cells (B-lymphocytes and T-cytotoxic cells) in nine of twelve recipients of fresh-frozen meniscal allografts. The effect of an immune response on graft incorporation is unknown; however, such a reaction may modulate graft-healing, incorporation, and revascularization.

Graft Biology

Most information about basic graft biology has been derived from animal studies. Meniscal grafts are repopulated by host-derived cells that appear to originate from the synovial membrane. Arnoczky et. al.[7] demonstrated that deep-frozen grafts undergo incomplete cellular repopulation, with the central core of the graft often remaining hypocellular or acellular (Fig. 2). Animal studies have demonstrated active collagen remodeling by the cells that repopulate the meniscus, with uncertain effects on graft material properties[52]. The long-term ability of the cells that repopulate an allograft to synthesize appropriate matrix proteins and maintain the extracellular matrix is unknown. Jackson et al.[53] demonstrated diminished glycosaminoglycan content of meniscal allografts in a goat model. Transplanted menisci also undergo

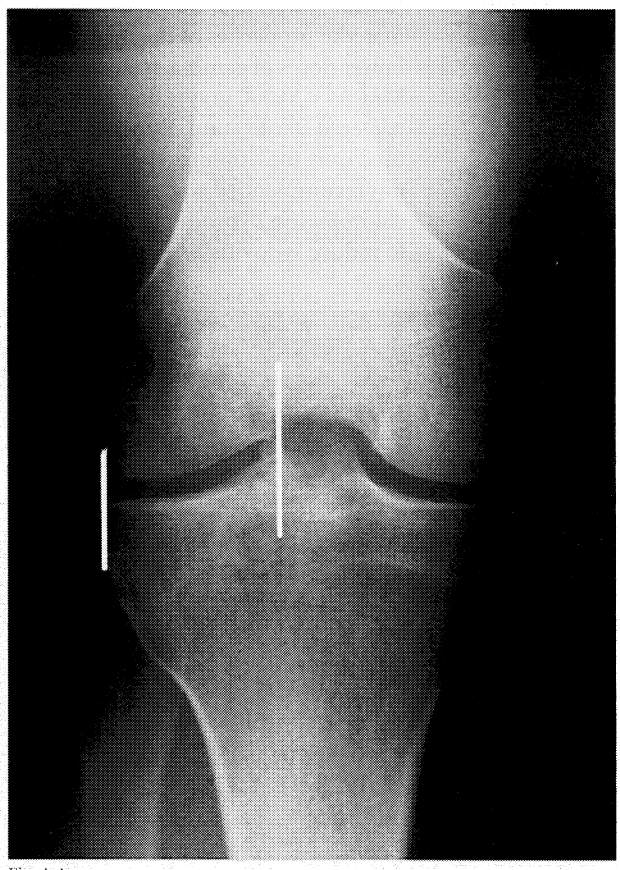


Fig. 4-A

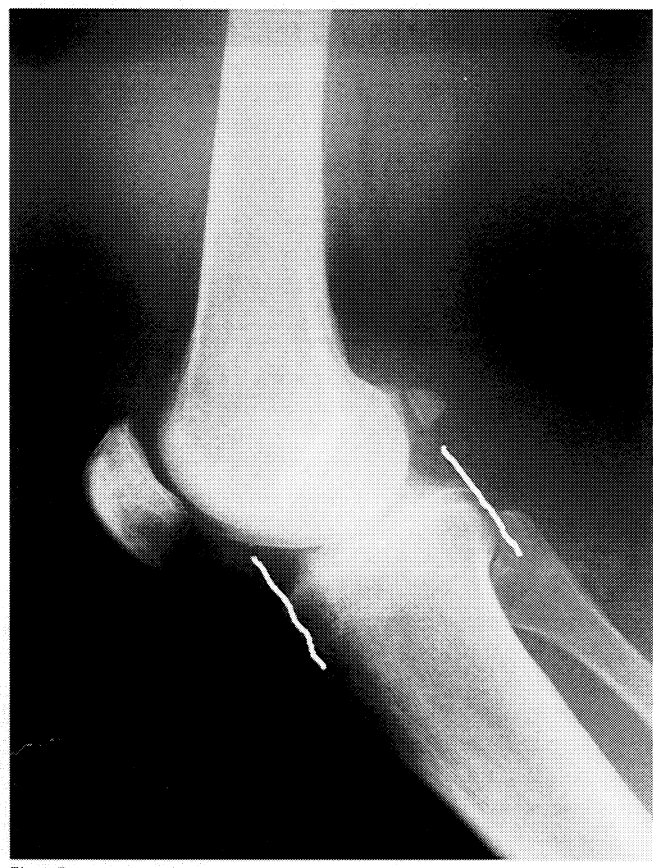


Fig. 4-B

Meniscal sizing is performed by first correcting for magnification. Then the meniscal width (Fig. 4-A), in the coronal plane, is calculated on the anteroposterior radiograph by measuring the distance from the peak of the tibial eminence (medial or lateral) to the respective tibial metaphyseal margin and ignoring marginal osteophytes. Meniscal length (Fig. 4-B), in the sagittal plane, is determined on the lateral radiograph. The medial meniscal length is considered to be 80% and the lateral meniscal length is considered to be 70% of the sagittal length of the tibial plateau—i.e., the distance measured at the joint line between a line parallel to the anterior aspect of the tibia and one tangential to the posterior plateau margin and perpendicular to the joint line.

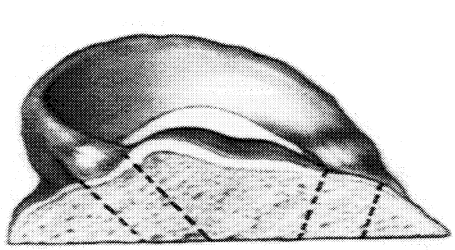
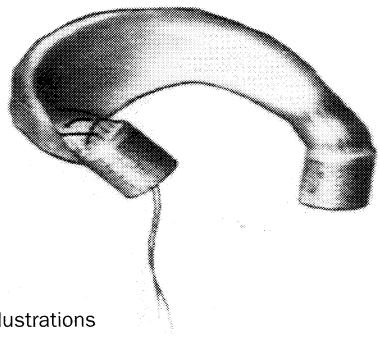


Fig. 5-A



Figs. 5-A, 5-B, and 5-C Double-bone-plug technique. (Illustrations courtesy of CryoLife, Kennesaw, Georgia. Reprinted with permission.).
Fig. 5-A Graft preparation.

gradual, incomplete revascularization, with new capillaries derived from the capsular and synovial attachments[53].

Rodeo et al.[51] examined biopsy specimens of intact and failed meniscal transplants in patients and reported incomplete cellular repopulation with active remodeling of the tissue, with more cells at the periphery. The repopulating cells had several phenotypes: mononuclear/synovial cells, fibroblasts, and fibrochondrocytes. Noyes and Barber-Westin[54] examined biopsy specimens of failed meniscal transplants and reported that the cells appeared more fibroblastic than fibrochondrocytic.

It is not known if the cells in a viable graft (fresh or cryopreserved) survive. A goat study demonstrated replacement of donor cells with host-derived cells following transplantation of fresh meniscal grafts[36]. Using histochemical techniques, de Boer and Koudstaal[55] examined three failed cryopreserved transplants from human patients and found an absence of cellular proliferation. At this time, there is no evidence that the extra expense and logistic difficulties associated with fresh or cryopreserved tissue are warranted. Additional studies are critical to improve our knowledge of biologic incorporation of meniscal allografts and the important interaction between biologic and biomechanical factors during graft incorporation.

Patient Evaluation

Not uncommonly, patients who have had an open or arthroscopic meniscectomy report nearly immediate and complete resolution of symptoms followed by a subtle increase, over time, in ipsilateral joint-line pain, activity-related swelling, generalized aching affected by changes in the ambient barometric pressure, and occasionally giving-way and crepitus. A thorough history, including the mechanism of injury, associated injuries, and previous treatments such as ligament reconstruction or management of articular cartilage lesions, should be elicited.

A physical examination is essential to look for concomitant disorders (e.g., malalignment or ligament deficiency) that would modify treatment recommendations. The location of previous incisions is noted and may provide evidence of prior meniscectomy. An effusion may or may not be present. Typically, patients have tenderness along the ipsilateral joint line and may have palpable osseous change along the

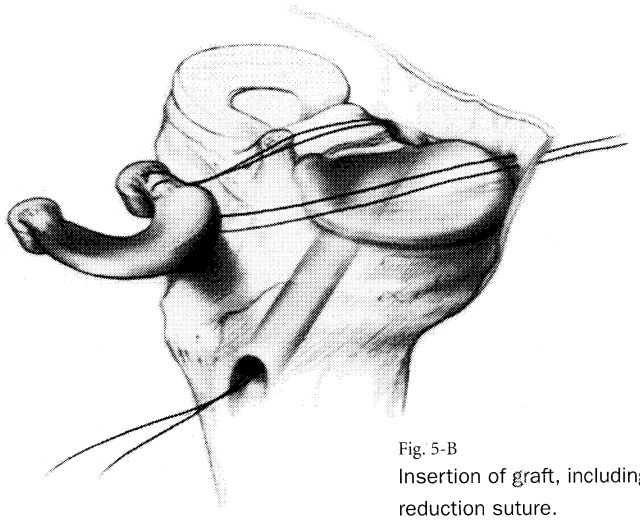


Fig. 5-B
Insertion of graft, including reduction suture.

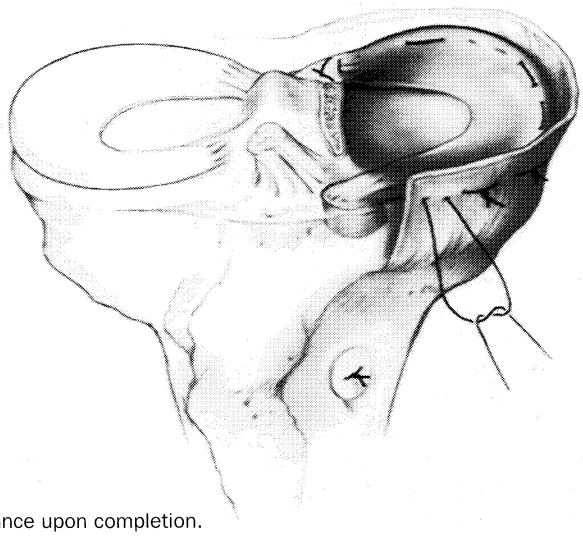


Fig. 5-C
Appearance upon completion.

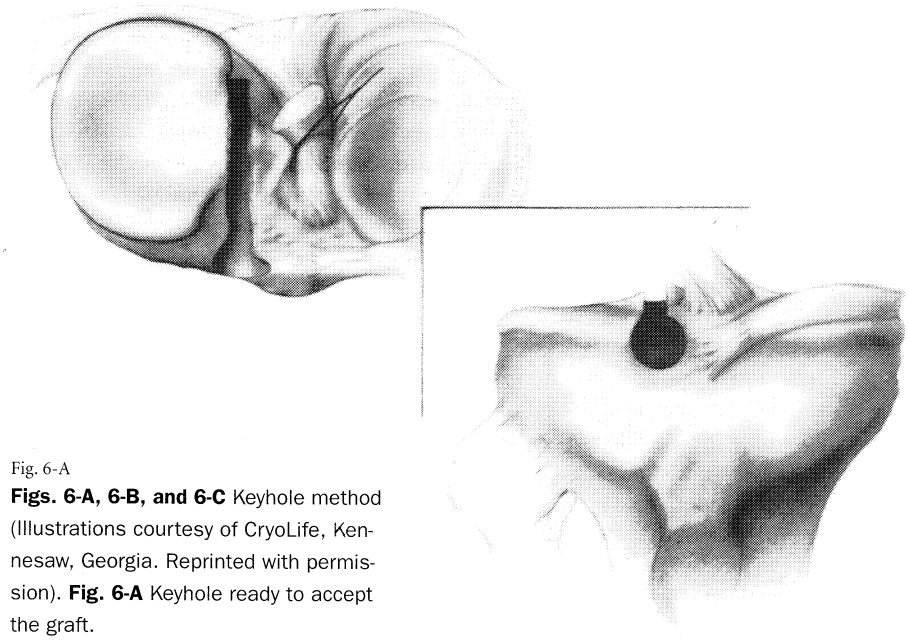


Fig. 6-A

Figs. 6-A, 6-B, and 6-C Keyhole method (Illustrations courtesy of CryoLife, Kennesaw, Georgia. Reprinted with permission). **Fig. 6-A** Keyhole ready to accept the graft.

edge of the femoral or tibial condyle. If the patient is to receive a meniscal transplant, motion should be normal because only minor degrees of arthritic change are considered acceptable in a candidate for meniscal transplantation.

Diagnostic imaging is required and should begin with a standard weight-bearing anteroposterior radiograph of both knees in full extension, a non-weight-bearing 45° flexion lateral radiograph, and an axial radiograph of the patellofemoral joint. Additionally, a 45° flexion weight-bearing posteroanterior radiograph is recommended to help identify subtle joint-narrowing that traditional extension views may fail to identify (Figs. 3-A and 3-B)[56]. The physician may need to order special studies, such as a long-cassette mechanical axis radiograph if there is any degree of clinical malalignment or magnetic resonance imaging if there is suspicion of chondral injury. If joint-space narrowing is seen on the 45° flexion weight-bearing posteroanterior radiograph, magnetic resonance imaging is rarely necessary. Generally, magnetic resonance imaging should be reserved for difficult cases in which the diagnosis remains unknown, especially when radiographs are completely normal or when previous operative reports are unavailable to determine the status of the articular cartilage or the extent of a prior meniscectomy. Techniques include two-dimensional fast spin-echo, and three-dimensional fat suppression with and without intra-articular gadolinium[57]. When questions remain about the source of symptoms, a three-phase technetium bone scan can be useful to assess for increased uptake in the involved compartment.

Indications

Ideally, transplantation of a meniscal allograft is indicated in symptomatic patients with a prior meniscectomy, persistent pain in the involved compartment with intact articular cartilage (i.e., less than grade III)[58], normal alignment, and a stable joint. There is no upper chronological age limit, but generally patients who are older than fifty to fifty-five years already have a degree of arthritis that contraindicates the procedure. Simultaneous or staged ligament reconstruction or realignment procedures are performed as indicated. Just a few degrees of deviation toward the involved compartment compared with the alignment in the contralateral limb is an indication for osteotomy. Serious articular disease (i.e., late grade III or IV) and radiographic signs of flattening of the femoral condyle or marked osteophyte formation are associated with inferior results and are considered the most common contraindications to meniscal transplantation. Localized chondral defects should be treated concomitantly. Additional contraindications include inflammatory arthritis, obesity, and previous infection.

Specific Clinical Scenarios

Lateral meniscectomy: Because the lateral meniscus makes a greater contribution to load-sharing than the medial meniscus does, patients more commonly present with early and rapid degeneration following lateral meniscectomy than they do following medial meniscectomy[14]. This is especially true for women with knees in valgus alignment. A previous isolated lateral meniscectomy remains a relatively common indication for meniscal transplantation in appropriately selected symptomatic patients.

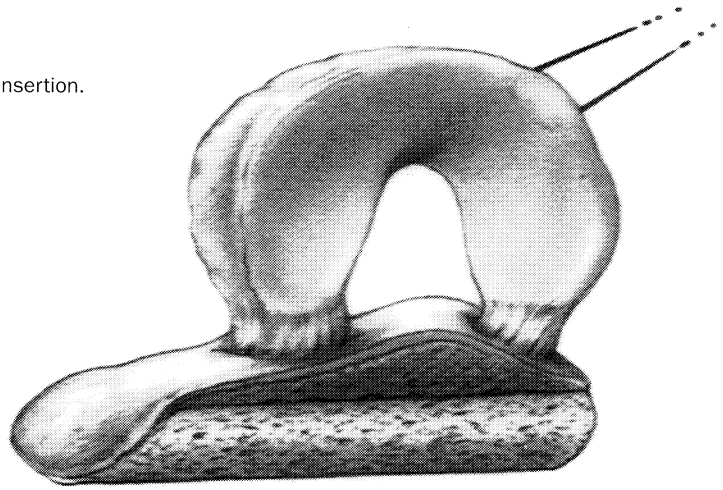


Fig. 6-B

Graft prepared for insertion.

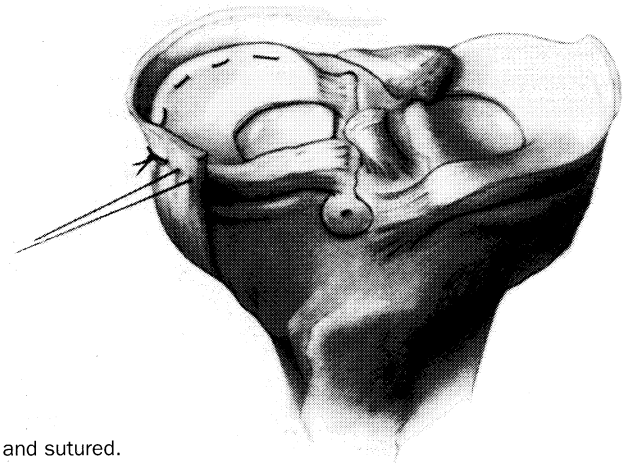


Fig. 6-C
Graft in place and sutured.

Anterior cruciate ligament deficiency: Patients with chronic anterior cruciate ligament deficiency who have had a prior medial meniscectomy may demonstrate excessive sagittal plane or rotational laxity because of the loss of the stabilizing effects of the posterior horn of the medial meniscus[19,20]. These patients often present with ipsilateral joint-line pain and giving-way. Additionally, a high index of suspicion is required when a patient who has had a reconstruction of the anterior cruciate ligament presents with progressive graft elongation in the setting of a prior medial meniscectomy[59]. These patients may respond favorably to allograft meniscal transplantation and will occasionally require revision of the anterior cruciate reconstruction.

Axial malalignment: When secondary varus or valgus deformity develops in a patient who has had a meniscectomy, it can be treated with staged or concomitant high tibial or distal femoral osteotomy, respectively. The order of the procedures depends on the surgeon and the patient, but meniscal transplantation should not be performed without correction of the malalignment. Typically, patients older than forty to forty-five years of age have an osteotomy first and then have a meniscal implant if the osteotomy fails to provide sufficient pain relief. Alternatively, patients may respond favorably to a concomitant osteotomy and allograft transplantation depending on their age, degree of malalignment, and severity of symptoms. With limb alignment reported to play a role in outcome, osteotomies have recently been recommended more commonly, but there is still no consensus on the indications for those procedures[55,60].

Chondral injury: Patients with ipsilateral chondral injury typically have the defects treated simultaneously with the meniscal transplantation, depending on the size, location, depth, and previous treatment of the defects[61-64]. Untreated focal chondral or osteochondral defects can lead to early failure of a meniscal transplant or to persistent symptoms unrelated to the meniscal transplant[65]. The rehabilitation (e.g., continuous passive motion or non-weight-bearing) following these combined procedures is usually guided by the technique of the cartilage restoration rather than by the meniscal transplant.

The recently meniscectomized knee: Management of patients who remain asymptomatic despite a recent or remote history of meniscectomy remains controversial. Typically, these patients are educated about the symptoms associated with secondary arthrosis and are followed annually, with 45° posteroanterior radiographs and occasionally three-phase technetium bone scans evaluated for progression of joint-narrowing[66]. The timing of allograft transplantation in

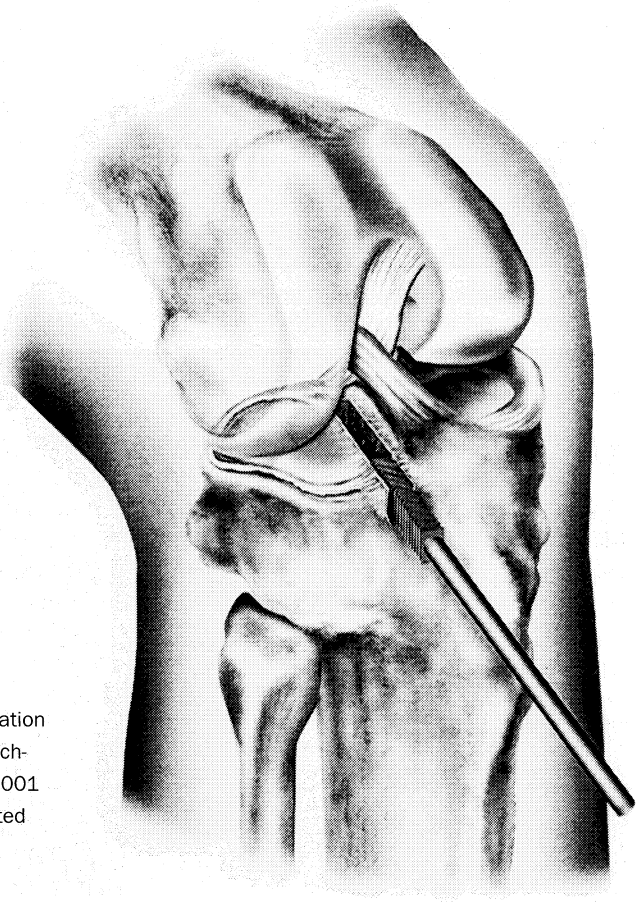


Fig. 7
Tibial trough method. (Illustration courtesy of Regeneration Technology, Alachua, Florida. ©2001 Neill Biomedical Art. Reprinted with permission.)

these patients is typically related to the onset of clinical signs and symptoms.

Allograft Sizing

Meniscal allografts are side and compartment-specific. While magnetic resonance imaging may be used with relative accuracy, plain radiographs are most commonly used to size allografts[67,68]. 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 utilized by the tissue provider to minimize the chance of a size mismatch. If, perioperatively, the graft is judged by the surgeon to be severely undersized or oversized, or if the surgeon is presented with the incorrect meniscus altogether (e.g., a medial rather than a lateral meniscus or a left rather than a right meniscus), the meniscus should not be used. Small size mismatches can be handled with only minor modifications and are likely to have minimal effects on anatomic restoration, but accurate sizing remains important to maximize the chondroprotective effect of the graft[69].

Most commonly, the technique described by Pollard et al.[68] is used for meniscal sizing (Figs. 4-A and 4-B). The meniscal width is determined on an anteroposterior radiograph, after correction for magnification, on the basis of a 1:1 relationship to the distance from the center of the respective tibial eminence to the periphery of the tibial plateau. 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. For example, if the tibial plateau measures 38 mm from the me-

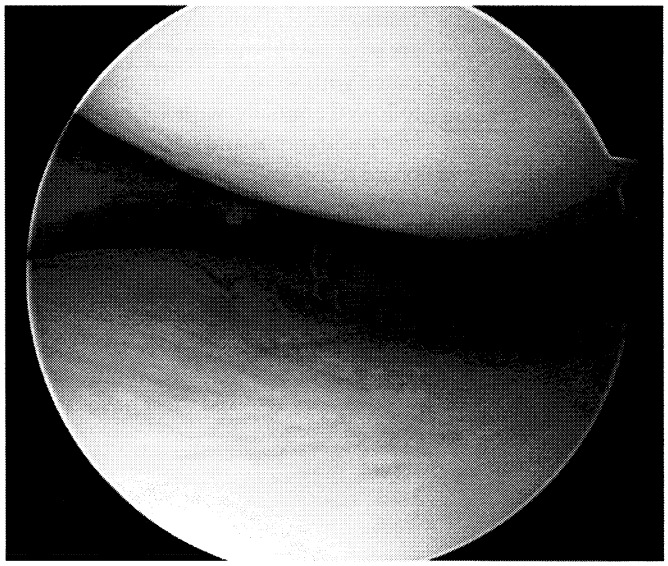


Fig. 8-A

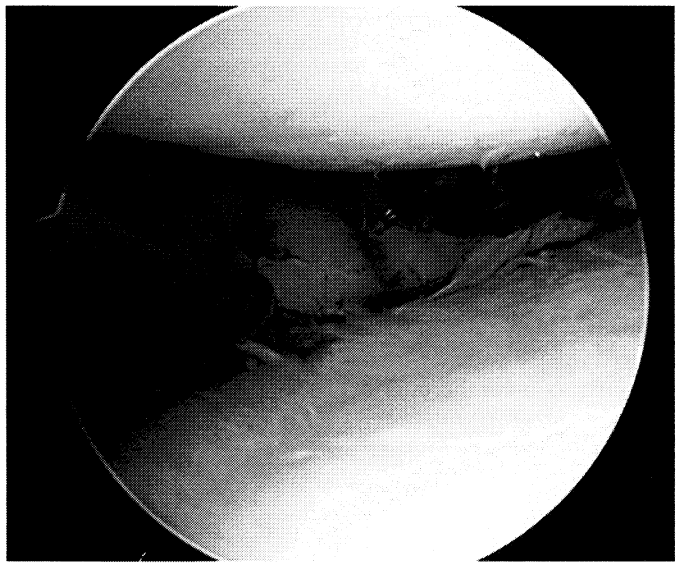


Fig. 8-B

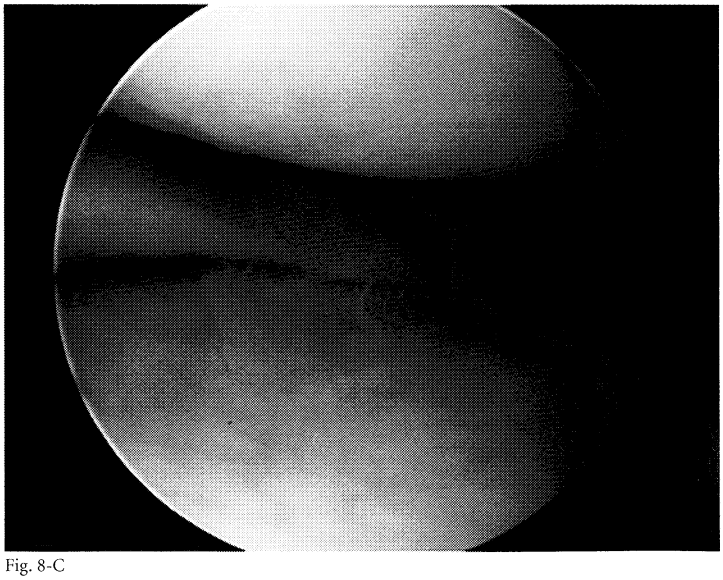


Fig. 8-C

Arthroscopic views of the knee of an eighteen-year-old woman following a subtotal medial meniscectomy (Fig. 8-A), after treatment with a medial meniscal allograft (Fig. 8-B), and at six months following implantation as seen on second-look arthroscopy (Fig. 8-C). There is complete peripheral healing and no evidence of meniscal shrinkage.

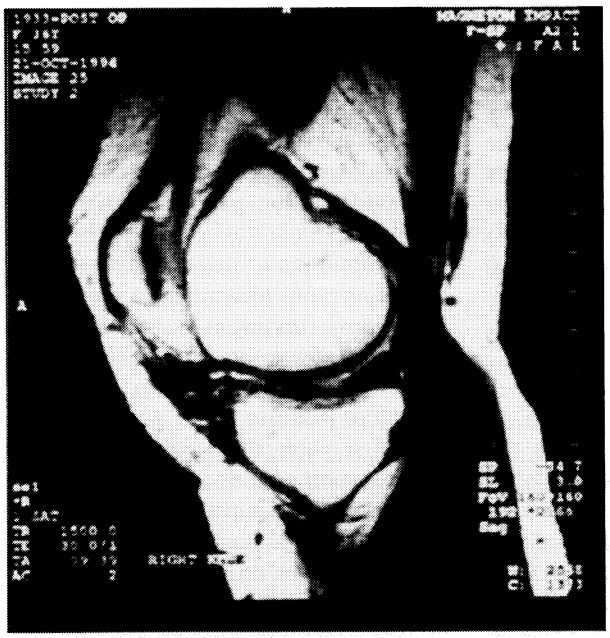


Fig. 9
Magnetic resonance imaging scan of a meniscal allograft at six months postoperatively, demonstrating the graft to have a normal position and size with minimal signal change at the host-graft junction (Reprinted, with permission, from: Carter TR. Meniscal allograft transplantation. Sports Med Arthrosc Rev. 1999;7:57.)

dial tibial eminence to the periphery of the tibia on an anteroposterior radiograph with 5% magnification, then the width of the required meniscal graft is 36 mm (38 × 0.95). If the sagittal length of the tibial plateau from anterior to posterior is 50 mm on a lateral radiograph with 5% magnification, then the length of the required medial meniscal graft is 38 mm ([50 × 0.95] × 0.8). With use of this technique, size mismatch occurs <5% of the time.

Surgical Technique

The meniscus can be implanted with use of either an open or an arthroscopically assisted technique. Although the results of the two methods have been reported to be similar, arthroscopic techniques are routinely used because of the reduced surgical morbidity[4,43,60,70-72]. Independent of technique, it is essential that the meniscus be placed in an anatomic position if it is to replicate an intact host meniscus.

Anchoring of the anterior and posterior horns with bone is essential to provide a functional meniscus. Although it is technically easier to secure the graft with soft tissue alone, research has indicated that load transmission is superior when the graft is secured with bone[17,18,73]. The most common methods involve use of either bone plugs or a bone bridge in the form of a trough or slot or a "keyhole" (Figs. 5-A through 7). The general principles are similar for all of the methods and have been presented in detail elsewhere[74-77]. The initial steps for medial and lateral meniscal transplantation are similar and are performed in the ipsilateral compartment only. The host meniscus is debrided arthroscopically to a 1 to 2-mm peripheral rim until punctate bleeding occurs.

The host tibia is prepared to receive the graft. There is a general consensus that, with implantation of a lateral meniscus, a bone bridge (i.e., a keyhole or slot) should be used because the distance between the horns is only 1 cm or less. Unlike the situation with a medial meniscus, use of bone plugs with a lateral meniscus presents a high risk of tibial tunnel communication with compromised fixation[75]. Although bone plugs are most commonly used for medial meniscal transplants, because the distance between the horns is much greater than that on the lateral side, agreement about the use of bone plugs for the medial meniscus is not as universal as the consensus that they should not be used for lateral meniscal transplants. Proponents of bone plugs on the medial side point out the variability in the anterior horn attachment site and the ability to make minor modifications in position[78,79]. Proponents of a bone bridge point out the ease of insertion and relative maintenance of the anatomic relationship between the anterior and posterior horns. Thus, while a bone bridge is commonly used on the lateral side, the medial side can be reconstructed with either a bridge or plugs, depending on the surgeon's preference.

Passage of the graft into the knee is challenging and is made easier with several steps. Reducing the tibial spine and performing a modified low notchplasty between the fibers of the posterior cruciate ligament and the medial femoral condyle facilitate posterior plug passage on the medial side. Expanding the trough or keyhole by 1 mm and meticulously debriding residual soft tissue facilitate bone-bridge passage on the lateral side. A traction suture placed in the posterior portion of the graft helps the surgeon to pull the meniscus into the knee and maintain its proper orientation.

A standard meniscal repair exposure positioned in line with the respective femoral epicondyle, with one-third of the incision situated proximal to the joint line and two-thirds situated distal to it, is required to protect the neurovascular structures during inside-out meniscal repair.

Eight, nine, or 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, the anterior horn bone plug is press-fit into a blind tunnel ideally reamed in the center of the footprint of the host anterior horn after the meniscus is secured posteriorly. Minor adjustments in position are made as required. All-inside bioabsorbable devices are a reasonable choice to secure the most posterior aspect of the meniscus to minimize the risk of neurovascular injury, but their pull-out strength is less than that of vertical sutures and they provide only single-point fixation[80,81].

Advanced Techniques

High Tibial Osteotomy

All soft-tissue preparation and the osseous portions of the meniscal transplant technique are performed first and

then followed by the osteotomy. Osteotomies should be performed as far distally as possible. Rigid fixation is required to allow the tibia to tolerate introduction of the meniscal graft and the valgus moment required for arthroscopic meniscal repair following the osteotomy. Proximal screw placement under fluoroscopic guidance is helpful to direct screws away from the previously prepared meniscal tunnels or trough.

Reconstruction of the Anterior Cruciate Ligament

With the medial double-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 lateral 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 without compromising the anatomic position of the anterior cruciate reconstruction avoids confluence between the tunnel and the lateral slot. The meniscal bone bridge may be partially compromised without untoward effects during creation of the tibial tunnel. Use of a hamstring graft for the reconstruction of the anterior cruciate ligament may facilitate graft passage.

Occasionally, patients have combined varus alignment, anterior cruciate ligament deficiency, and an absent medial meniscus with relatively intact articular cartilage. These patients are typically managed with reconstruction of the anterior cruciate ligament 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 done only when a patient has persistent symptoms following recovery from the initial procedure.

Autologous Chondrocyte Transplantation and Osteochondral Grafting

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[64].

Rehabilitation

Postoperative treatment following allograft meniscal replacement is similar to that after autogenous meniscal repair, but recommended programs vary widely, from immediate institution of a full range of motion and unlimited weight-bearing to maintenance of the lower limb in full extension and non-weight-bearing for six weeks[4,82,83]. Theoretically, a more conservative protocol is advisable because of the higher loads associated with a freshly transplanted meniscus in a joint with early degenerative change.

Most surgeons allow a range of motion from 0° to 90° with protected weight-bearing with a hinged knee immobilizer during the initial four to six weeks. Thompson et al.[8] found that the meniscus shows little movement from 0° to 60° of knee flexion. As flexion is increased, the meniscus translates anteriorly, resulting in displacement from the capsule and stress on a posterior repair. With clinical confirmation of this finding, limiting flexion to 90° seems appropriate. Weight-bearing is allowed, but it is commonly restricted because of concerns of graft-weakening during revascularization in the early postoperative stage[84,85].

Early-phase rehabilitation is otherwise similar to protocols following reconstruction of the anterior cruciate ligament. Achieving full extension is an early goal, and isometric exercises are encouraged to limit muscle atrophy. Closed-chain kinetic exercises are begun with weight-bearing, but forced flexion and pivoting activities should be avoided.

It is generally agreed that patients should have nearly normal strength and proprioception before strenuous activities and sports are allowed, but opinions vary greatly with respect to the time-frame, which ranges from four to twelve months. It is not known if meniscal transplants will survive high-impact activities. Despite recommendations for caution, patients often attempt high-level activities because of the relief of symptoms afforded by the procedure. Most surgeons recommend a program that allows running at four to six months and full activities at six to nine months.

Clinical Results

The first meniscal allograft procedures were combined with complete knee transplantation during limb-sparing reconstructions almost a century ago[86]. In 1984, Milachowski et al.[43] performed the first isolated meniscal allograft procedure. Several series have been reported since that time.

In 1989, Milachowski et al.[43] reported on their initial twenty-two patients treated with a total of six fresh-frozen and sixteen freeze-dried grafts. At an average of fourteen months postoperatively, second-look arthroscopy to assess eighteen grafts demonstrated peripheral healing of fifteen and failure of only three (one fresh-frozen graft and two freeze-dried grafts had to be removed). Macroscopically, the fresh-frozen grafts appeared more normal than the freeze-dried grafts.

The first series that we know of in the American literature was reported by Garrett et al. in 1991[87] and was expanded on in 1993[70], with two to seven-year results reported for forty-three patients. Most of the reconstructions were complex, with twenty-four concomitant reconstructions of the anterior cruciate ligament, thirteen osteotomies, and eleven osteochondral allografts; only six patients had an isolated meniscal transplant. A fresh graft was used in sixteen patients and a cryopreserved graft, in twenty-seven. Twenty-eight patients underwent second-look arthroscopy, at two months to two years after the meniscal grafting. Twenty of these patients were asymptomatic and were considered to have a successful result, with healing of the meniscus to the host and without meniscal shrinkage or

degeneration. The eight failures were related to grade-IV chondromalacia at the time of the second-look arthroscopy. The fifteen patients who did not have repeat arthroscopy were asymptomatic and considered to have a clinically "silent" outcome. One of the six patients who had only a meniscal transplant had failure of the graft. No differences were found between the results associated with the fresh and cryopreserved grafts. Other than graft failure, no complications were noted.

The largest series of which we are aware was reported by Noyes et al.[54,88], who evaluated ninety-six fresh-frozen irradiated grafts implanted in eighty-two patients. Most grafts were secured with bone at the posterior horn only, and none had both horns attached by bone. The mean age of the patients was twenty-nine years (range, thirteen to forty-five years). Twenty-nine menisci had to be removed less than two years after the operation, leaving sixty-seven menisci (fifty-seven medial and ten lateral) in sixty-three patients followed for a mean of thirty months (range, twenty-two to fifty-eight months). Arthroscopy and/or magnetic resonance imaging were performed on all patients to evaluate healing. Overall, 9% of the ninety-six grafts healed, 31% were partially healed, and 58% failed clinically. Further analysis revealed a significant relationship ($p < 0.001$) between failure and the degree of arthrosis of the knee. Of the knees that were considered to be normal on postoperative magnetic resonance imaging, 70% healed and 30% were partially healed. Knees with grade-IV arthrosis had a 50% failure rate. The relatively high failure rates in this series reflect the importance of using nonirradiated menisci, of selecting patients with no worse than grade-III arthrosis, and of maintaining the osseous attachment of the meniscal horns.

Zukor et al.[89] reported the results of implantation of thirty-three fresh meniscal and osteochondral allografts. At one year postoperatively, twenty-six grafting procedures were considered successful. There were no failures attributable to meniscal pathology. All ten of the menisci that were examined with second-look arthroscopy were stable at their peripheral attachment.

Van Arkel and de Boer[72] prospectively studied a group of twenty-three patients treated with a cryopreserved meniscal transplant and followed for two to five years. Twenty patients had a satisfactory result, and peripheral healing was demonstrated in all but three of the patients examined with second-look arthroscopy. Histological analysis demonstrated revascularization with viable meniscal chondrocytes. There were three failures, at less than twenty-four months, associated with uncorrected malalignment.

Cameron and Saha[60] reported on sixty-seven irradiated menisci implanted without bone insertions, many in patients with advanced unicompartmental arthritis. Despite this, at an average of thirty-one months (range, one to 5.5 years), 87% of the patients had a good or excellent result according to a 100-point functional knee score. The most frequent complication was a traumatic tear of the posterior horn, which occurred in six knees at a mean of twenty-one months postoperatively.

In 1999, the senior one of us (B.J.C.) and Harner[90] reported the results at a minimum of two years after implantation of twenty-two fresh-frozen menisci. Preoperatively, all patients had had at least moderate knee pain. Postoperatively, 88% reported marked relief of this pain, with an overall knee rating of 87 points (range, 75 to 100 points) according to the University of Pittsburgh Knee Scale. Self-reported overall knee function was nearly normal or better in twenty-one cases and abnormal in one.

Since 1997, the senior one of us has performed fifty-three meniscal transplants (thirty isolated and twenty-three combined procedures), and twenty have been followed for more than two years. Excluding four failures that occurred in patients with grade-IV arthrosis, the remaining sixteen knees were rated as nearly normal (twelve) or normal (four) according to the IKDC (International Knee Documentation Committee) rating system.

Carter[4] reported the results at a minimum of two years (range, twenty-four to seventy-three months) after implantation of forty-six cryopreserved grafts. Second-look arthroscopy in thirty-eight cases demonstrated four with failure, four with visible shrinkage of the graft, and two with progression of arthritis. Thirty-two of the thirty-eight patients demonstrated relief of pain and improvement in activities, and only one patient indicated an unwillingness to undergo the procedure again under similar circumstances.

Stollsteimer et al.[71] reported on twenty-two patients treated with a total of twenty-three cryopreserved allografts and followed for one to five years. All patients reported substantial pain relief. Compared with the normal menisci, the allografts demonstrated an average shrinkage of 37% (range, 0% to 69%) as seen on magnetic resonance imaging. This finding, however, was not associated with an adverse outcome. Other series of patients treated with a meniscal transplant[74,77,91] are summarized in Table I.

It is evident that 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 degree of arthrosis at the time of allograft transplantation is possibly the most important factor, with advanced arthrosis associated with the highest failure rates[54,70,92]. Using magnetic resonance imaging, Rodeo[77] 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[55,60]. Van Arkel and de Boer[72] attributed their three graft failures to uncorrected limb alignment. Cameron and Saha[60] performed osteotomy in thirty-four of sixty-three patients. By realigning the knees to "unload" the involved compartment, they achieved a success rate comparable with that

TABLE I Clinical Results of Meniscal Allograft Transplantation

Study	Duration of Follow-up	Outcome
Milachowski et al.[43]	14 mo (mean)	19 (86%) of 22 successful
Garrett[70]	2-7 yr	35 (81%) of 43 successful
Noyes et al.[54,88]	30 mo (mean); 22-58 mo (range)	56 (58%) of 96 failed clinically
Van Arkel and de Boer[72]	2-5 yr	20 (87%) of 23 successful
Cameron and Saha[60]	31 mo (mean); 12-66 mo (range)	58 (87%) of 67 successful
Gobel et al.[74]	2 yr (minimum)	17 (94%) of 18 successful
Carter[4]	34.5 mo (mean); 24-73 mo (range)	45 (88%) of 51 successful
Rodeo[77]	2 yr (minimum)	22 (66%) of 33 successful (14 [88%] of 16 with bone fixation and 8 [47%] of 17 without bone fixation)
Rath et al.[91]	5.4 yr (mean); 2-8 yr (range)	14 (64%) of 22 successful

in the group as a whole, with a good-to-excellent result in 85% and 87%, respectively.

Several authors have reported graft shrinkage at second-look arthroscopy or on follow-up magnetic resonance imaging[4,43,70,91]. Most, however, have found this to be an infrequent occurrence (Figs. 8-A, 8-B, and 8-C)[70,74]. It is not known why grafts shrink. Shrinkage could be due to a subclinical immune response with graft-remodeling during cellular repopulation, a poor-quality graft, excessive graft-loading during healing, the surgical technique, the extent of knee arthrosis, or some variable not currently recognized.

Some magnetic resonance imaging scans have demonstrated that the grafts look similar to a normal meniscus (Fig. 9), whereas others have shown signals consistent with degenerative changes[4,71,77,88]. The use of magnetic resonance imaging as a postoperative tool to determine graft-healing is still questionable, and second-look arthroscopy is considered necessary to define the exact extent of graft-healing[72,93-96].

Whether meniscal grafts delay or prevent arthritis is not known. Unfortunately, many investigators have not reported the findings on weight-bearing radiographs, while others have made radiographs at only early postoperative time-points. Rath et al.[91] reported that the compartment space of the involved knees of eleven patients averaged 5.2 mm before surgery and 4.5 mm at two to eight years after it. Carter[4] stated that only two of forty-six knees demonstrated radiographic progression at a mean of 34.5 months (range, twenty-four to seventy-three months) postoperatively, but their results were not quantified. To our knowledge, a longer-term prospective, randomized study comparing the progression of arthritis with and without an allograft has not been completed.

Overview

It is evident that meniscal allograft transplantation is a viable option for the treatment of symptomatic patients with a meniscus-deficient knee and no more than grade-II or early grade-III arthrosis, provided that other rigid inclusion criteria are met. Clinical studies have demonstrated the effectiveness of this procedure in alleviating pain and swelling and in improving knee function. Results are poor in patients with advanced arthrosis, and this remains the primary contraindication to the procedure. Allograft meniscal transplantation is technically challenging, and the indications are relatively uncommon as most patients initially do well following meniscectomy. However, symptomatic patients with appropriate indications for allograft meniscal transplantation should expect to do well postoperatively in terms of a predictable reduction in pain and an ability to increase activity levels. This observation is supported by the results of early and midterm follow-up studies. Only further study will clarify the long-term results of meniscal allografts as well as their role in preventing the progression of secondary osteoarthritis in the involved compartment.

Brian J. Cole, MD
Rush Cartilage Restoration Center, Rush Medical College, 1725 West Harrison Street, Suite 1063, Chicago, IL 60612. E-mail address: bcole@ortho4.pro.rpslmc.edu

Thomas R. Carter, MD
1492 South Mill Avenue, #113, Tempe, AZ 85281. E-mail address: sargecarter@home.com

Scott A. Rodeo, MD
Sports Medicine and Shoulder Service, The Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021. E-mail address: rodeos@hss.edu

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