More recently, increasing attention has been turned toward the preservation and restoration of the medial and lateral menisci of the knee. The literature is replete with studies that cite the important biomechanical roles that the menisci play in shock absorption and load distribution across the knee in addition to contributing to stability, joint congruence, articular cartilage nutrition, lubrication, and proprioception. Published data supports that meniscal attrition after subtotal meniscectomy could be associated with degenerative processes in adjacent articular cartilage surfaces. Despite this body of work, arthroscopic meniscectomy remains one of the most commonly performed orthopaedic procedures. The development of an increasingly more sophisticated and scientific understanding and approach to knee problems and, in particular, the natural history of the meniscectomized knee has raised concern for the risk of late degenerative arthrosis. Multiple other factors have continued to heighten interest in meniscal surgery, including the trend in our society for all age groups to place greater emphasis on fitness and remaining active. This has raised the demand for normalizing knee function, not only after injury, but also at extended follow up. Patients, the media, and clinicians alike all focus more attention on the treatment as well as the prevention of osteoarthritis. Furthermore, as more advanced technical capability has evolved as far as knee surgery is concerned, there is an increasing tendency to carry out more comprehensive arthroscopic and reconstructive surgical methods. Expanding surgical indications and demand now exists for anterior cruciate ligament (ACL) reconstruction, articular cartilage biologic resurfacing, and correction of axial malalignment as well as meniscal preservation or replacement surgery. Interest in the meniscus continues to remain in the forefront of basic scientific work, clinical study, and novel technology development. The purpose of this publication is to review the current and potential future approaches to meniscal pathology, including decision-making and indications for meniscal resection versus repair, and to report on several of newest devices and methods for repairing meniscal tears and replacing and transplanting meniscal tissue.

**RESECTION VERSUS REPAIR**

Patients who present with symptomatic knee pathology, including pain, effusion, catching, locking, and persistent focal joint line tenderness, that is refractory to conservative treatment could be candidates for meniscal surgery. The decision to debride or resect a meniscal tear is then based on numerous clinical parameters. Tear pattern, geometry, site, vascularity, size, stability, tissue viability or quality, associated pathology, and surgery must all be taken into account when considering whether resection or repair is performed. Age might not necessarily be an absolute factor in determining who is a candidate for repair, although with advancing age, predominantly irreparable tear types (degenerative patterns) and a lack of tissue viability (attenuation and deformation) tend to result in more meniscal resections and less repairs. Most importantly, patient preference must considered after thorough counseling regarding procedural risks.
versus benefits, recovery, and rehabilitation as well as the outcomes and natural history of selected treatment options. In general, in the short term, meniscal resection is associated with less recovery time and restrictions, whereas in the long term, repair could be associated with a more favorable prognosis. However, this concept might not always be the case.

WHY NOT REPAIR THE MENISCUS?

The question that could be posed is why would a meniscal tear not be repaired? Patient issues, including recovery time and retear risks, could play a role in certain cases in which an expeditious and more predictable return to work or sport is preferred. Technical issues could affect the decision of certain surgeons to resect rather than repair, particularly in cases in which the procedural hassle of carrying out the repair and learning curve associated with placing a repair or suture device is deemed more difficult than removal. Concerns and questions regarding the true clinical success of repair and whether a repaired meniscus will ever heal and biomechanically function as normal have been raised by those who predominantly advocate resection over repair. Finally, extended follow-up studies have indicated that in certain patients, the natural history of the knee after partial meniscectomy might not necessarily be associated with a poor prognosis and could in fact be quite benign compared with if a total meniscectomy is performed.11-13

WHY REPAIR THE MENISCUS?

These points then raise the question, why would every effort be made to repair a meniscal tear? Primarily, advocates of repair cite the laboratory work that has indicated that load transmission, contact stresses, tibiofemoral patholaxity (particularly in knees that have associated ACL deficiency) are all altered by the excision of the meniscus.1,2,7 Furthermore, published meniscal repair results have supported favorable success at extended follow up in over 70% to 90% of patients.16-19 Regarding natural history studies, conflicting results have been reported as a result of the lack of controlled studies. Outcome, and specifically functional and radiographic prognosis, after meniscus resection is related to several associated factors that must be considered and stratified to accurately predict postmeniscectomy morbidity. Those variables include whether the meniscectomy is defined as a circumferential resection that extends into and through the circumferential band at the periphery of the meniscus. Violation of the circumferential band ultrastructure leads to significant disruption of the meniscal biomechanics with alteration in the normal distribution and dissipation of compressive loads and hoop stress conversion. This is in contrast to a segmental resection in which less meniscal tissue is removed and/or the circumferential fibers and structure are not disrupted. Segmental partial meniscectomies can be associated with a more favorable prognosis over time as far as chondral wear is concerned.20 Another significant variable that plays a role in the outcome after meniscal resection is axial mechanical alignment. Several studies have concluded that if the mechanical axis is noted to fall within the ipsilateral meniscectomized compartment, then a poorer outcome could be associated with meniscal resection at extended follow up.21,22 A third prognosticator could be defined by the extent of associated pathology.10,11 One study of 119 patients who had undergone partial meniscectomy and were evaluated at 12 years after the procedure found 95% success in cases in which no associated adjacent chondral lesions or pathology was noted at the index surgery compared with 62% overall success in patients with associated chondral lesions.14

Index surgery can be associated with a more favorable prognosis compared with those that have associated adjacent pathology.10,11 Ligament deficiency has also been shown to have an effect on outcome after meniscectomy; in 167 patients followed up at 20 years after partial meniscectomy, 92% were rated successful if they had an intact ACL compared with 74% if the ACL was deficient.23 In conclusion, long-term prognosis after meniscal resection is more favorable in cases in which there is no associated adjacent chondral or ligament pathology and in which a segmental rather than circumferential partial meniscectomy is performed in a compartment that does not have the mechanical axis of the extremity passing through it. Conversely, patients with ipsilateral chondral lesions and malalignment in association with ligament patholaxity and a circumferential resection could have a poorer outcome over time. Analysis and consideration of these factors might be useful in preoperative counseling of patients and decision-making regarding whether resection versus repair should be performed. It could also be valuable in discussing long-term risks and prognosis after meniscal resection surgery.

INDICATIONS FOR RESECTION, RASPING, OR REPAIR

The indications for meniscal surgery include symptomatic meniscal tears that result in persistent pain, effusion, catching, and/or locking that are refractory to
nonsurgical treatments. The specific indications for meniscal resection versus repair or rasping could be dependent on multiple clinical variables and prognosticators; however, ultimately, reparability of the actual tear site could determine which procedure is performed. Table 1 lists the indications for resection, repair, and rasping.

### MENISCAL RESECTION TECHNIQUES

Traditional instrumentation and techniques for carrying out an arthroscopic meniscectomy have included the use of various angled handheld basket punches, scissors, and rotary mechanical shavers. More recently, in an attempt to address the efficiency of the procedure, improve the contouring of the resection edge, and increase the access to the posterior horns, especially in tight medial compartments, other meniscal resection technologies have been introduced. The use of bipolar radiofrequency devices has been reported using radiofrequency meniscal ablation probes. The advantages of this technique include increased access to the more difficult-to-reach meniscal tears and rapid and effective meniscal resection with proposed smoother-edge contouring. There is also the theoretical and potential beneficial effect of thermal annealing of the residual tissue, especially in the complex degenerative tear types such as horizontal meniscal tears. Disadvantages include the high cost of the probes as well as the potential for significant thermal injury, not only to the perimeter native meniscal tissue, but also the adjacent articular cartilage. Another novel technology has been recently introduced that is based on the use of arthroscopic instrumentation using high-speed fluid-jet tissue ablation devices. These devices offer the potential to more precisely and rapidly cut and resect torn meniscal tissue without the risk of thermal injury using a focused, high-pressure fluid stream and direct outflow system. Clinical experience with these devices is limited, and further work is required to validate their efficacy and document their safety.

### MENISCAL RASPING TECHNIQUES

In meniscal tears that are incomplete or incomplete tears that are found to be stable, stimulation of healing without resection or suture placement can be carried out though rasping and trephination. Several authors have reported on these techniques. Optimal tear selection includes nondegenerative peripheral red-red vertical tear patterns in patients with an associated acute ACL injury that are less than 7 to 10 mm in length and associated with less than 3 to 5 mm of excursion. Tears of the lateral meniscus noted to be posterior horn avulsions, vertical tears posterior to the popliteus tendon, and incomplete radial or flap tears have been reported to be associated with high clinical success rate if left “in situ” at the time of ACL reconstruction. The fate of nondegenerative “stable” (unable to be displaced into the intercondylar notch) medial meniscal tears noted at the time of ACL reconstruction has been studied after treatment with abrasion and trephination. The technique includes use of a shaver or meniscal rasp to aggressively roughen the actual tear site and adjacent parameniscal synovial tissue to stimulate vascularity for meniscal healing. In addition, trephination can be carried out to create vascular access channels using either a proprietary coring device or 18-gauge spinal needle to punc-

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Site</th>
<th>Size</th>
<th>Excursion</th>
<th>Tissue viability</th>
<th>Prognosticators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oblique flaps, radial, degenerative complex, horizontal</td>
<td>Inner (white–white)</td>
<td>NA</td>
<td>&gt;7-10 mm</td>
<td>Deformed frayed, nonviable</td>
<td>ACL intact, no malalignment, no chondral lesions</td>
</tr>
<tr>
<td>Longitudinal/vertical bucket-handles</td>
<td>Peripheral (red–red), middle (red–white), inner (white–white)</td>
<td>&gt;5-mm displaced into notch</td>
<td>&gt;3-5 mm</td>
<td>Minimal deformation, holds repair device, viable</td>
<td>Associated ACLR, associated chondral procedure, axially maligned</td>
</tr>
<tr>
<td>Incomplete longitudinal</td>
<td>Red–red posterior horn, lateral meniscus</td>
<td></td>
<td></td>
<td></td>
<td>ACL intact, well-aligned, no chondral lesions</td>
</tr>
</tbody>
</table>

Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament repair; NA, not applicable.

---

**Table 1. Indications for Meniscal Resection, Repair, or Rasping**

<table>
<thead>
<tr>
<th>Pattern</th>
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Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament repair; NA, not applicable.
ture the meniscal tear site and adjacent tissue, thereby promoting capillary ingrowth from the more vascularized peripheral tissues.

**MENISCAL REPAIR TECHNIQUES**

In cases in which a meniscal tear is found to be repairable and surgical indications are met, then preservation of the meniscus is preferred, particularly in younger, active individuals undergoing associated ACL reconstruction and/or articular cartilage-resurfacing procedures. Numerous techniques can be used to carry out the repair, depending on the tear type, site, size, displacement and, most importantly, surgeon preference. Various arthroscopic-assisted meniscal repair methods have significantly evolved over the last 20 years and include outside-in, inside-out, all-inside, and all-arthroscopic fixator implant and suture-based techniques. In addition, combinations of several methods or hybridized techniques can be used.

**Arthroscopic Outside-In Technique**

Outside-in meniscal repair techniques have been reported in the literature to be useful in repairing meniscal tears in the mid-one-third and anterior horn regions. The technique reduces the risks of neurovascular injury by referencing the placement of suture passing needles well anterior to the posterior bundle and under direct arthroscopic visualization. The technique can be carried out using several 18-gauge spinal needles placed 3 to 5 mm apart or a corresponding suture-passing needle system with wire-looped retrievers. The needles are passed from outside to inside through the tear starting anteriorly for initial reference. The meniscal tear site is perforated either on the inner (or superior femoral) or outer (or inferior tibial) surfaces. If an absorbable monofilament suture is used such as polydioxanone (Ethicon, Somerville, NJ), then the individual suture strands can be pulled out of the arthroscopic portal using an arthroscopic grasper, and an intercalary “mulberry” knot can be tied, which is then withdrawn back into the joint and tensioned at and up to the meniscal tear site. Nonabsorbable suture materials can also be used in combination with specific outside-in meniscal repair instrumentation. This allows the placement of more variable suture patterns, including horizontal, oblique, and vertical mattress patterns. The outside-out repair technique requires that after the sutures are passed across the tear, a 1- to 2-cm skin incision be made surrounding the sutures and down to the capsule to properly tension the sutures and tie them down on or against the adjacent capsule. The advantages of the outside-in technique include the relatively less invasive nature of the technique and safe access to the middle and anterior horns with the ability to place versatile suture patterns using various suture materials. In addition, this technique can be used in peripheral meniscocapsular tears because it anchors the meniscus to the capsule. It is also useful as an adjunct hybrid method for reducing and provisionally stabilizing displaced bucket-handle tears that are being repaired using other methods (inside-out or all-arthroscopic). The disadvantages include limited and/or difficult access to the posterior horns and the need to make an accessory incision to capture and tie down the sutures (Figs 1A, B).

**Arthroscopic Inside-Out Technique**

Inside-out meniscal methods incorporate both arthroscopic passage of sutures and open posterolateral and posteromedial capture of the repair needles and suture with knots then tensioned down against the corresponding capsule. Anatomically matched and contoured arthroscopic cannulae are used intra-articularly and usually placed from a contralateral portal to ensure safe needle passage away from the neurovascular structures. Extra long suture needles are then passed though the cannulae across the tear and depending on whether a single- or double-lumen cannula system is used, vertical, horizontal, and oblique sutures patterns can be achieved. The accessory incisions, which can extend for 4 to 6 cm are best made before the passage of the needles. The incisions are made with the knee in 90° of flexion beginning at the level of the joint line and extending one-third above and two-thirds below the joint. A contoured retractor is inserted anterior to and deep to the gastrocnemius and facilitates protection of the adjacent soft tissues. The posteromedial incision is made above the level of the sartorius muscle, which is retracted posteriorly with the sartorial branch of the saphenous nerve. The posterolateral incision is made just posterior to the lateral collateral ligament staying anterior to the biceps femoris tendon. After placement of the repair sutures, they are then tied to the corresponding adjacent suture limb over the capsule while arthroscopically viewing the tensioning and seating of the meniscus tear site. The medial meniscal repair sutures are tied with the knee in 20° of flexion, whereas the lateral sutures are tied with the knee in 90° of flexion. The advantages of the inside-out technique include its proven clinical success and the ability to place vertical
mattress sutures associated with optimal strength characteristics with access to the middle one-third and, to a lesser extent, the posterior horns. In meniscal allograft cases, this technique optimizes the anchoring of the transplanted tissue to the native meniscal rim and capsule. The disadvantages include the concern and difficulty associated with needle passage through the posterior horns and in close proximity to the neurovascular bundle as well as the morbidity related to accessory posteromedial and posterolateral incisions and dissection.

**All-Inside Technique**

Several authors have reported on an all-arthroscopic method of repairing posterior horn tears through a posteromedial portal using arthroscopic suture passage techniques and knot tying. A 70° arthroscope with viewing carried out through the intercondylar notch facilitates the technique. This method eliminates the need for any accessory incisions, but is most applicable to more peripheral tear patterns, particularly vertical tears (the more commonly repaired patterns). The advantages of all-inside suturing include safe access to the posterior horns and the minimally invasive nature of the approach. The disadvantages include the increased technical difficulty of arthroscopic suture management and knot tying as well as the limited application to specific meniscal tear patterns and sites.

**All-Arthroscopic Fixator Technique**

Multiple meniscal repair fixator devices have become available that have expanded the potential methods of an all-arthroscopic approach. Most of the devices are based on a reverse-barbed fishhook design that maintains apposition and reduction of the tear fragments. Various devices differ in geometry, size, polymer composition, and insertion techniques. In general, the surgical technique of repairing meniscal tears using fixators is similar in that the tear site is prepared by rasping and the surrounding meniscocapsular junction is excoriated to promote a fresh vascularized surface. The tear is provisionally reduced and the tear distance from the periphery is measured to allow precise selection of the appropriately length fixator. The fixator(s) must be inserted perpendicular to the tear to maximally compress the tear site. It is important that there be enough meniscal tissue on both sides of the tear fragment for the device to obtain a balanced tissue purchase and ensure optimal function. Tears that involve peripheral capsular detachments and repair of meniscal allografts might not represent clinical cases in which these devices provide optimal fixation. Each fixator is inserted at 3- to 5-mm intervals apart, and care must be taken to ensure that the fixator head is seated flush to the surrounding menis-
cal tissue and countersunk to reduce the risk of articular cartilage injury. Table 3 lists the various first-generation fixator devices, including design and composition profiles. There are noncannulated headed barbed devices (Arrow, Linvatec, Largo, FL); cannulated low-profile barbed devices (BioStinger, Linvatec); noncannulated “J-T”-shaped devices (Fastener, Mitek, Westwood, MA); noncannulated headless threaded screw devices (Clearfix Screw, Mitek); noncannulated headless, barbed, and reverse barbed devices (Dart, Arthrex, Naples, FL); and barbed staples (Staple, Arthrotek, Warsaw, IN) (Table 2).

All-arthroscopic meniscal repair devices have continued to rapidly evolve. The initial experience with these devices has been good, and several published reports of clinical success comparable to inside-out methods have been encouraging. However, other authors have described complications associated with the use of these first-generation devices, including retained polymer fragments, foreign body reactions, surrounding soft tissue inflammation, and chondral injury. Furthermore, laboratory studies have indicated that most of the fixator devices are associated with strength profiles more closely approximating horizontal suture configurations and significantly lower than vertical mattress suture. In response to those clinicians who contend that meniscal repair using suturing techniques could represent a more optimal method for obtaining a secure repair, newer devices has been introduced that allow for all-arthroscopic placement of suture-based implants (Table 3).

### Updated First-Generation Devices

#### Updated Arrow Designs: The Meniscus Arrow (Linvatec), initially released by the Bionx company in 1996, had an original design that included a 4-mm long “T”-shaped head with a 1.1-mm diameter shaft of three lengths (10, 13, and 16 mm). The shaft of the device possesses reverse barbs at right angles to the “T” head and 90° offset to each other. The Arrow can be inserted manually using a variable curved-angle insertion cannulae system or a mechanical “Crossbow” with multiple implant devices preloaded in a magazine. The original device was composed of self-reinforced polymerized levorotatory polylactic acid (PLLA). PLLA, an alpha polyester composed of lactic acid that degrades through hydrolysis. As water permeates the polymer, the molecular bonds are cleaved with resultant breakdown of the implant. There are two forms of PLLA based on its asymmetric molecular form, an “L” levorotatory and “D” dextrorotatory stereoisomer configuration. PLLA is estimated to have a resorption profile of 36 to 60 months, PDLLA is

### Table 2. Meniscal Repair Fixators

<table>
<thead>
<tr>
<th>Device</th>
<th>Sizes</th>
<th>Material</th>
<th>Resorption</th>
<th>Strength* (load to failure)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BioStinger</td>
<td>10, 13, and 16 × 1.25 mm diameter</td>
<td>Injection-molded PLLA</td>
<td>36 mo</td>
<td>56.6 N (13 mm)</td>
<td>New Hornet cannulated insertion device</td>
</tr>
<tr>
<td>Fastener</td>
<td>6 and 8 mm</td>
<td>Prolene (polypropylene) or PDS</td>
<td>PDS 6-16 wk</td>
<td>30 N (8-mm Prolene)</td>
<td>12°, 24° and 34° curved inserters</td>
</tr>
<tr>
<td>Clearfix</td>
<td>10 × 2.0 mm diameter</td>
<td>PLLA</td>
<td>18 mo</td>
<td>32.5 N</td>
<td>Cannulated with variable thread pitch</td>
</tr>
<tr>
<td>Dart</td>
<td>10, 12, and 14 × 1.3 mm diameter</td>
<td>Amorphous PDLLA copolymer</td>
<td>9 mo</td>
<td>Not tested</td>
<td>Double reverse barbs: flexible; new dart stick</td>
</tr>
<tr>
<td>Staple</td>
<td>11 and 13 mm</td>
<td>Lactosorb 82% PLLA 18% PGA</td>
<td>12 mo</td>
<td>27 N</td>
<td>Double-pronged fixation</td>
</tr>
</tbody>
</table>

*Study reference, Rimmer and Nawama. Abbreviations: PLLA, polymerized levorotatory polylactic acid; PDLLA, polyactic acid dextrorotatory “D” stereoisomer configuration; PGA, polyglycolic acid.
associated with a faster degradation profile. When the two stereoisomeric configurations are combined, the resultant copolymer possesses intermediate properties and characteristics between the two. The manufacturing process of a particular polymer also determines the mechanical strength and biochemical behavior of the implant. Several implant-machining methods can be used, including injection molding and the self-reinforcing proprietary techniques used in the production of the Arrow. Self-reinforced polymers are extruded and then stretched into alignment as the more amorphous polymer is drawn through a heated dye. This serves to orient the polymer and improve its initial implant strength.

In late 2000, the polymer composition of the Arrow was changed to 96% PLLA combined with 4% of the polylactic acid dextrorotatory “D” stereoisomer configuration (PDLLA; 96/4), making it more amorphous with different degradation and mechanical properties than pure PLLA. This, in effect, would impart a quicker resorption time to the 96/4 copolymer implants. More recently, the actual device was redesigned to include a lower-profile geometry and is known as the Contour Arrow (Linvatec). The Contour Arrow is composed of an even more flexible and amorphous polymer consisting of 80% PLLA and 20% PDLLA (80/20). The implant design was changed from the 1.1-mm thick “T” head to a lower profile rounded and contoured 0.7-mm head, adding barbs to the entire length of the shaft. The overall updated design will presumably result in a lower profile and safer fixator that is stronger, less stiff, and associated with a shorter resorption time (Fig 2A, B).

**Polysorb Meniscal Stapler XLS:** The Polysorb Meniscal Stapler released by Surgical Dynamics (Surgical Dynamics, Norwalk, CT) as the SDsorb Meniscal Stapler in 1997 is now distributed by USS Sports Medicine (United States Surgical, North Haven, CT). The Stapler, which is comprised of an injection-molded copolymer comprised of 82% PLLA and 18% polyglycolic acid (PGA) consists of two barbed 10-mm fixation posts linked by a 4-mm braided absorbable suture. The suture is contained within and spans the length of the rigid barbed fixation posts. The copolymer is reportedly resorbed in approximately 15 months. The device, which provides two points of

### Table 3. Next-Generation Meniscal Repair Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Sizes</th>
<th>Material</th>
<th>Resorption</th>
<th>Strength*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour Arrow</td>
<td>10, 13, and 16 × 1.1-mm</td>
<td>Self-reinforced copolymer</td>
<td>12-24 mo</td>
<td>33.6 N (result for 13-mm first-generation device)</td>
<td>New redesigned lower profile head, fully barbed shaft and copolymer multiloaded cartridge</td>
</tr>
<tr>
<td></td>
<td>diameter, 0.7-mm head</td>
<td>80% PLLA 20% PDLLA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysorb</td>
<td>2 10-mm fixation posts with 4-</td>
<td>82% PLLA 18% PGA</td>
<td>15 mo</td>
<td>31.4 N</td>
<td>New longer implants lower profile inserter</td>
</tr>
<tr>
<td>Meniscal</td>
<td>mm suture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stapler XLS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BioStinger</td>
<td>10, 13, and 16 × 1.25-mm</td>
<td>Injection-molded PLLA</td>
<td>36 mo</td>
<td>56.6 N (13 mm)</td>
<td>New Hornet cannulated insertion device</td>
</tr>
<tr>
<td></td>
<td>diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FasT-Fix</td>
<td>2 5-mm suture anchors</td>
<td>PLLA or polylactone and 0</td>
<td>NA</td>
<td>104 N, 72.1 N</td>
<td>New slide trigger, trochar tip, cannula and waxed tip suture; vertical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nonabsorbable suture</td>
<td></td>
<td></td>
<td>mattress suture possible</td>
</tr>
<tr>
<td>RapidLoc</td>
<td>2 suture anchors</td>
<td>PLLA Tophat and backstop</td>
<td>NA</td>
<td>43 N, 35.6 N</td>
<td>New PDS quicker resorbable Tophat; suture compression possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ethibond or Panacryl suture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meniscal Viper</td>
<td>6.43-mm suture passer</td>
<td>No. 2-0 nonabsorbable suture</td>
<td>NA</td>
<td>NA</td>
<td>All-arthroscopic knot tying required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(FiberWire)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Abbreviations: PLLA, polymerized levorotatory polylactic acid; PDLLA, polylactic acid dextrorotatory “D” stereoisomer configuration; PGA, polyglycolic acid; NA, not available.

**Table 3. Next-Generation Meniscal Repair Devices**
meniscal fragment fixation, is inserted using a redesigned insertion system that includes a preloaded disposable double-barrel insertion cannula. The cannulae are now available in lower-profile precurved tips with straight and 8° upswept configurations (with left and right as well as beveled-tip configurations pending). In addition, a reusable zone-specific templating system will be released, which will allow for easier cannula selection.

**BioStinger:** The BioStinger was the first cannulated fixator device introduced with a lower profile head that could be seated flush with the surrounding meniscal tissue (Linvatec). The device is 1.25 mm in diameter and contains four rows of reverse barbs on all sides of the shaft and is available in 10-, 13-, and 16-mm lengths. The BioStinger is violet-colored for improved arthroscopic visualization and is comprised of 100% injection-molded PLLA with a resorption profile of 36 to 60 months (Fig 3A). Three generations of insertion devices have been introduced with the BioStinger, including an original manual inserter that was followed by a mechanical gun and more recently a plunger-type inserter known as the “Hornet,” which is available in three dedicated sizes corresponding to the three available implant sizes, which are initially preloaded on the color-coded inserters (Fig 3B).

**Second-Generation Devices**

**RapidLoc:** The RapidLoc device represents one of the newest generation of all-arthroscopic suture-based meniscal repair devices. It was released by Mitek in 2001 and is an integrated needle delivery system consisting of a leading 5 × 1.5-mm PLLA “backstop” anchor with attached suture that is inserted across the tear site and seated extracapsularly. In sequence, a second attached PLLA anchor (with overlying pretied, self-sliding, integrated knot) known as a “tophat” is cinched down on the suture toward the backstop and right up to the tear site thereby compressing the tear between the two anchors connected by the suture. The “tophat,” which is 4.5 mm wide and 0.25 mm thick, is then seated intra-articularly on the femoral side of the meniscus, and compression across the tear site can be obtained by using an arthroscopic knot pusher to

![Figure 2. (A) Meniscus Arrow and (B) Contour Arrow. (Reprinted with permission.34)](image-url)
further seat the knot. The RapidLoc has been recently updated and is now available with a PDS intraarticular “tophat.” This development addresses concerns about having an intra-articular PLLA implant that might not be as rapidly absorbed as the underlying extended absorption suture (if Panacryl suture is used), thus potentially resulting in a loose body or chondral abrasion (Fig 4). The delivery needles are available in 12° and 27° curved configurations and the suture is available in nonabsorbable 2-0 Ethibond (Ethicon, NJ) or extended resorption Panacryl, which is reported to retain 86% of its tensile strength at 4 weeks postimplantation, 63% at 6 months, and 34% at 1 year (Mitek). Fixation strength, specifically mean load to failure of the RapidLoc device, has been reported to be approximately 43.28 N in a freshly harvested porcine animal model (Barber, personal communication, 2002).

**FasT-Fix:** The FasT-Fix Meniscal Repair System represents, along with the RapidLoc, another second-generation suture-based device incorporating all-arthroscopically placed implants and attached repair suture. The FasT-Fix is in part a design expansion of the original T-Fix system introduced by Smith and Nephew in 1994. It incorporates a two 5-mm polyacetal anchors with attached 0 nonabsorbable braided synthetic polyester suture integrated in sequence with a preloaded, pretied, self-sliding and self-locking knot and delivered in an arthroscopic 16.5-gauge insertion needle (Figs 5 and 6). The integrated delivery needle is available in a straight or 22° curve. The system includes a split-sheath insertion cannula and separate knot pusher/suture cutter. The variable positioning choices for the needle insertion allow for arthroscopic placement of vertical mattress suture configurations and, in addition, the use of sutures placed across the tear site and anchored extracapsularly introduces compression across the tear (Fig 6). In 2002, design advances included the release of the FasT-Fix system improved and sharper trocar-tipped delivery needles, waxed-tip suture for easier threading, and more ergonomic and easier-to-use needle delivery insertion handpieces and split-sheath cannulae. These design changes have been introduced to improve the operative delivery of the implant and to reduce several of the technical pitfalls and learning curve that has been associated with the original device. In 2003, the FasT-
Fix suture anchors became available in a bioresorbable injection molded and annealed PLLA with a projected resorption profile of 36 to 60 months, and the integrated knot pusher/suture cutter is now available in a curved design. Questions regarding the ultimate location of these anchors in the knee has been addressed in a published cadaveric study in which 50 first-generation T-Fix devices were placed in six fresh-frozen specimens to investigate the placement location and final resting position of the extracapsular suture anchors. The authors found that 36 of the 50 anchors were seated just beyond the capsular layer, well within a safe zone and distance from the neurovascular structure.64

Regarding where these newer suture-based repair devices fit in as far as strength profiles are concerned, the FasT-Fix, when placed using a vertical configuration, has been reported to have mean load to failure of 72.1 N as studied in a freshly harvested adult porcine model (Barber, personal communication, 2002). In a study using human menisci and comparing two FasT-Fix devices with two 13-mm Arrows, the FasT-Fix exhibited the higher mean load-to-failure at a mean 104 N compared with the Arrow at 49 N. In the same study, the FasT-Fix was also compared with two 0 nonabsorbable vertical mattress sutures, and the FasT-Fix demonstrated superior strength to the inside-out suture (mean values of 104 v, 102 N) with similar stiffness (mean of 7.7 N/mm for both the vertical suture and the FasT-Fix).65

The advantages of these newer devices could be that they represent a method of achieving a secure all-arthroscopic meniscal repair using sutures to compress the tear site and without the risks associated with the more rigid and brittle fixator devices. The disadvantages include their cost as well as the fact that all of these devices are associated with the potential morbidity inherent in introducing significant learning curves into our operative experience. It is important to point out that no technique is necessarily easier or quicker if its learning curve and technical pitfalls are not satisfactorily worked out. A study designed to evaluate the learning curves associated with the use of these devices has been reported. In a comparison of the FasT-Fix with the RapidLoc in a cadaveric model, several potential pitfalls were described and suggestions were made to improve the technique.66 The study illustrated that there is no one best technique and all are associated with a certain degree of difficulty.

**Meniscal Viper:** The Meniscal Viper is a disposable arthroscopic suture-passing instrument with accompanying knot pusher and suture cutter that allows for the all-arthroscopic introduction of nonabsorbable suture through posterior horn tears (Arthrex, Largo, FL). Suture loops can be placed through the meniscus tear site and the device can be loaded with No. 2-0 Fiber-Wire suture (Arthrex). The instrument incorporates an advancing suture-grasping needle that pierces the meniscus tear and retrieves the suture that is looped and seated on the tip of the curved jaw of the device. The suture that is passed through the meniscus then re-
quires arthroscopic knot-tying with placement of a “racking hitch” knot and alternating half-hitches to secure the repair. The advantages of the Meniscal Viper include the ability to place vertical mattress sutures through an all-arthroscopic method, possibly with a reusable device and an optimal strength suture of choice. Its disadvantages include the need for arthroscopic knot-tying and difficulty with accessing tight medial compartments because the intra-articular tip of the device has overall a outer diameter height of approximately 6.43 mm (Fig 7).

Meniscal Repair Rehabilitation

There is little scientific evidence to definitively support one specific postoperative rehabilitation protocol after meniscal repair. The wide range of techniques and variable devices, along with the fact that many repairs are carried out at the time of ACL reconstruction, limit valid conclusive advice on how to routinely proceed. This is further complicated by the evolving techniques that continue to be introduced. Several authors have reported on the clinical success of meniscal repair followed by an accelerated protocol emphasizing immediate range of motion, early weight-bearing, and return to sport or stressful activities within months of surgery. Other reports have pointed out that a more individualized approach should be followed based on the assessment and determination of which repairs are “at-risk” and protecting them postoperatively on a case-by-case basis. It seems that as more tears are repaired in possibly older patients and those repairs are carried out on more complex geometric tear patterns and not necessarily in association with ACL reconstruction, then individualizing the postoperative rehabilitation protocol might be warranted. At the very least, immediate full extension and flexion to 90° with protected early strengthening should be considered in most repairs. Regarding return to sports or strenuous work activities, most would agree that patients can return when their clinical examination reveals a corresponding nontender joint line in the absence of pain and effusion with full range of motion and restored strength.

SUMMARY

The approach to symptomatic meniscal tears is increasingly emphasizing preservation and repair. In cases in which resection is indicated, then proper counseling regarding prognosis and the risks for later postmeniscectomy-associated degenerative joint disease is essential. Newer methods continue to be introduced to address meniscal resection as well as repair. Devices that can provide a more efficient method of contouring or sealing a tear site are being developed and clinically tested, and could improve and refine our approach to meniscectomy. The numerous advances in all-arthroscopic meniscal repair have included the release of multiple repair devices that have simplified the approach to repair, reducing the invasiveness of the surgery. Concerns still exist regarding the associated pitfalls and morbidity associated with these newer repair techniques as well as the true strength and untested clinical performance of many of these devices. These repair methods have continued to rapidly evolve and improve, and there has recently been a trend toward the development of suture-based repair systems. These next-generation devices can combine the advantages of a minimally invasive all-arthroscopic delivery method with the compression strength of traditional inside-out suturing and could represent the “best of both worlds.” Despite all the novel methods, time-tested techniques using outside-in and inside-out methods remain excellent options and can be used adjunctively in combination with several of the newer devices. Several of the techniques can be used in hybrid repair constructs and as well in certain cases in which peripheral capsular detachment is encountered. Overall indications for the use of one technique over another could also be dependent on the types of tears that are repaired. In general, meniscal fixators and implants can be best used for vertical, longitudinal red-white tears that are associated with at least a 2- to 3-mm rim width to provide optimal barb-tissue contact. In addition, nondisplaced and nondeformed tears,
especially in cases in which concomitant ACL reconstruction is performed, could also represent good indications. Suture-based devices can be best used for repair of more complex tear patterns or less vascular tears (or avascular white-white tears) with less optimal tissue viability or with significant deformity or deformation as seen in large displaced bucket-handle tears (Table 4). As the techniques and devices continue to improve, the decision to select one technique or technologies over another should ultimately be based on surgeon preference and experience and steeped in safety and anticipated efficacy.

**UPDATE ON MENISCAL REPLACEMENT**

**The Collagen Meniscus Implant***

Tissue engineering is a relatively new discipline that has received much recent attention. Tissue engineering has provided a fundamental understanding and technology that has permitted the development of structures derived from biologic tissues. Biodegradable collagen matrices serve as one example of innovative new devices that have resulted from the discipline of tissue engineering. These collagen matrix materials have many positive features for use in preservation and restoration of meniscus tissue, including a controlled rate of resorption based on the degree of crosslinking, processing of the collagen can minimize any immune response, and the extremely complex biochemical composition of the normal meniscus can be closely approximated during the production process. If such a material could serve successfully as a scaffold for regeneration of new tissue, then much of the previously noted postmeniscectomy morbidity might be prevented or at least minimized.

The goals in the development of this collagen scaffold, known as the Collagen Meniscus Implant (CMI), included the ability to regenerate or regrow meniscus tissue in an effort to restore or preserve the critical functions of the meniscus. There were several criteria for design of the collagen meniscus implant, including the need for a material that would be resorbable over time so that as the collagen of the scaffold was metabolized, new tissue would have the opportunity to replace it. In addition, the CMI was required to maintain its structural integrity after intraarticular insertion for a period that would be adequate to support the new matrix formation and maturation. The implant had to be nonimmunogenic to minimize reactions that might cause rejection or destruction of the implant, so biochemical techniques were developed as part of the processing procedures to minimize such reactions. It was also important to design the implant so that it would be technically straightforward to implant surgically with a minimum of sizing considerations. The implant would have to be nonabrasive, not produce any wear particles, and not incite an excessive inflammatory response. Finally, it was extremely critical that the implant be nontoxic to the cells that invaded the scaffold and eventually produced the new matrix.

Hence, the hypothesis was that if one could provide such an environment, the meniscus fibrochondrocytes, or perhaps other progenitor cells, would migrate into the scaffold, divide and populate the scaffold, produce extracellular matrix, and finally lead to the regeneration of new meniscus-like tissue. This new tissue then would preserve and help restore the damaged meniscus cartilage and would function like the meniscus to be chondroprotective.

**COLLAGEN MENISCUS IMPLANT SURGICAL TECHNIQUE**

The CMI is fabricated from bovine Achilles tendons (Fig 8). The tendon tissue is trimmed and minced and then washed copiously with tap water to remove blood residue and water-soluble materials. Type I collagen fibers are purified using various chemical treatments such as acid-base and enzymatic processes to remove noncollagenous materials and lipids. The isolated type I collagen fibers then are analyzed for purity. After

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*The Collagen Meniscus Implant (CMI) is not available for sale or distribution in the United States. Studies described in this presentation were performed under a U.S. Food and Drug Administration (FDA) Investigational Device Exemption (IDE). The FDA has classified the CMI as an investigational device, and it can be used in the United States only within the standards set forth in the IDE.*

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**Table 4. Repair Techniques Indications**

<table>
<thead>
<tr>
<th>Repair Technique</th>
<th>Indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside-in sutures</td>
<td>Anterior horn tears, mid-third tears, radial tears, complex tears, reduction of bucket-handle tears</td>
</tr>
<tr>
<td>Inside-out sutures</td>
<td>Posterior horn tears, mid-third tears, displaced bucket-handle tears, peripheral capsular tears, meniscal allografts</td>
</tr>
<tr>
<td>Fixator implants (first-generation devices)</td>
<td>Posterior horn tears, tears with &gt;2 to 3 mm rim width, vertical/longitudinal tears</td>
</tr>
<tr>
<td>Suture-based devices (second-generation devices)</td>
<td>Posterior horn tears, mid-third tears, bucket-handle tears, radial tears</td>
</tr>
</tbody>
</table>
further processing, terminal sterilization is done by gamma irradiation.\textsuperscript{74,75}

The Collagen Meniscus Implant is placed using routine arthroscopic surgical procedures. The damaged meniscus tissue is debrided only until healthy tissue is reached. In those cases in which the debridement does not reach the red zone of the meniscus, a microfracture awl is used to perforate the host meniscus rim until a bleeding bed is assured. A special Teflon measuring device developed for this procedure is then used to measure the exact size of the defect. The collagen meniscus implant is measured and trimmed to the correct size on the sterile field of the operating environment. A posteromedial incision is made approximately 3 cm in length parallel and just posterior to the medial collateral ligament directly over the joint line so that the inside-out meniscus repair needles can be captured and the sutures tied over the capsule. A specially designed introducer containing the Collagen Meniscus Implant is inserted through the ipsilateral portal, and then a plunger pushes the implant out of the delivery device into the joint. When positioning is satisfactory, the implant is sutured to the host meniscus rim using standard inside-out techniques with zone-specific meniscus repair cannulae. Sutures are placed approximately 4 to 5 mm apart using size 2-0 nonabsorbable braided suture material. Sutures are placed in a vertical mattress pattern around the rim of the meniscus remnant, and a horizontal pattern is used in the anterior and posterior horns. Typically, 8 to 10 sutures are used to secure the implant in place. The sutures then are tied over the capsule in a standard manner (Fig 9).

\textbf{COLLAGEN MENISCUS IMPLANT RESULTS}

Eight patients underwent arthroscopic placement of the CMI to reconstruct and restore the irreparably damaged medial meniscus of one knee between December 1995 and July 1996. Seven patients had one or more prior medial meniscectomies, and one patient had an acute medial meniscus injury. Patients were observed with frequent clinical, serologic, radiographic, and magnetic resonance imaging (MRI) examinations for at least 24 months (range, 24-32 months) initially. As part of the initial study, all patients underwent second-look arthroscopy and biopsy of the CMI-regenerated tissue at either 6 or 12 months after implantation. All patients improved clinically from preoperatively to 1 and 2 years postoperatively based on pain, Lysholm scores, Tegner activity scale, and self-assessment. Second-look arthroscopy revealed tissue regeneration in all patients with apparent preservation of the joint surfaces based on visual observations. Histologic analysis of the CMI-regenerated tissue confirmed new fibrocartilage formation. Radiographs confirmed no progression of degenerative joint disease in the medial compartment.

As part of a long-term (5-6 years) follow-up study, all eight patients have returned for clinical, radiographic, and MRI examinations. Clinical outcome measurements are virtually unchanged from the 2-year follow-up examination. Radiographs confirm that the medial compartment chondral surfaces continue to be...
Collagen Meniscus Implant

Conclusions

Based on our personal experiences with the limited long-term feasibility study and the randomized, multicenter clinical trial, we conclude that the CMI is implantable, biocompatible, and bioresorbable. It supports new tissue regeneration as it is resorbed, and the new tissue appears to function similar to normal meniscus tissue. Based on the second-look procedures, the chondral surfaces are generally protected by the CMI-regenerated tissue. No serious or life-threatening complications directly related to the CMI have thus far been observed, and most patients are functioning well based on clinical examination and outcomes assessment. Similar positive European observations resulted in obtaining the European Union Regulatory Commission mark for the CMI in 2000. Regulatory approval was obtained in Japan, Australia, and Chile in 2002. Approval is pending in other non-U.S. countries at this time.

Meniscal Allograft Transplantation: Where Do We Stand?

Despite awareness of the meniscus’ importance to normal knee function, meniscectomy remains the most common orthopaedic procedure performed today. Emphasis on repair has led to preservation in many cases, but many menisci cannot be repaired or preserved. We know from natural history studies that even partial meniscectomy can lead to degenerative change. Total meniscectomy poses even more of a threat. Exactly how many and who specifically is at risk is unclear. This clinical problem is a challenge because historically we have had few “solutions” to offer the younger patient with a painful, meniscus-deficient knee in whom early arthritis could already be developing. Before meniscus replacement, treatment alternatives included symptomatic measures such as oral and injectable medications, arthroscopic debridement, realignment osteotomy, or arthroplasty. None of these options have been particularly effective for this group of patients.

History of Meniscus Transplantation

Meniscus transplantation was introduced by Milachowski in 1984 and has provided a means of definitively addressing symptomatic meniscal-deficient patients. In the United States, meniscus transplantation was first reported in a small series of six patients by Garrett in 1991. Initially performed using arthrotomy, the procedure has evolved with modifications based on refinements in technique and knowledge based on biomechanics. When properly indicated and performed, transplantation leads to good results in...
over 90% of patients. Meniscus transplantation has become an accepted and important tool in the clinical management of the symptomatic postmeniscectomy patient. Data from 2002 suggests that more than 4,000 transplants have been performed since 1991, with an estimated 800+ menisci implanted annually. It appears as though meniscus transplantation has become, to some degree, a mainstream alternative, notwithstanding the still relative infrequency with which it is performed.

Why Replace the Meniscus With Allograft Meniscus?

Many substitutes have been the object of experimentation in attempts to replicate normal meniscus form and function such as collagen scaffolds, tendon transplants, and synthetic polymers. However, only meniscal allograft has withstood clinical implantation with consistent success, seeming to provide some biomechanical function of the human meniscus. Allograft tissue in general has an established track record in limb-salvage reconstruction for tumor or trauma. Application of this experience to meniscal deficiency is logical. The tissue is relatively available and, unlike conventional organ transplantation, is essentially “immunologically privileged” as a result of human leukocyte antigens’ “protection” within a relatively acellular matrix.

Indications

There are two primary indications for meniscus transplantation. The first, and most common, indication is the symptomatic patient with pain in the affected meniscal-deficient compartment for whom non-operative treatment has been ineffective. Ideally, the patient’s knee is normally aligned, stable, and demonstrates little degenerative change. The patient understands and accepts risks associated with transplantation (disease transmission) and the fact that despite good clinical results, long-term biomechanical chondroprotection remains unproven. They are compliant with the restricted postoperative weight-bearing regimen and are willing/able to tolerate some activity modification in efforts to protect their “investment.”

Unfortunately, “ideal” patients are infrequent and, in reality, few patients meet these perfect criteria. Review of the literature shows that overall, only 20% of meniscus transplants are performed as “isolated” procedures. Of these, most have some degree of established chondral pathology. The remaining 80% have concomitant pathology that is surgically addressed. Concomitant procedures are most commonly performed for ligament insufficiency (most commonly ACL, but also posterior cruciate ligament, posterolateral insufficiency, and combined instability patterns), malalignment (varus in the medial and valgus in the lateral compartments), and chondral disease (isolated Outerbridge grade IV lesions with exposed subchondral bone).

The second most common indication for meniscus transplantation is in ACL-deficient patients undergoing reconstruction in whom meniscal deficiency could preclude satisfactory stabilization. Some patients cannot be adequately stabilized by ligament reconstruction alone. If performed with meniscus replacement, however, reconstruction can achieve a greater degree of stability and a more stable and functional knee.

Although discussed in the literature, there is no current role for treating the asymptomatic “at-risk” patient who has undergone a complete or near-complete meniscectomy. Enthusiasm for prophylactic implantation, particularly in young patients in which the meniscus has been nearly entirely removed, is understandable. This is particularly so because of the success clinically in treating symptomatic meniscal-deficient patients. Implantation before the development of irreversible chondral changes is compelling. However, we do not have sufficient long-term data to prove the legitimacy of this argument, and until that data is available, we would be subjecting these patients to unnecessary risks that could exceed those of “possible” degenerative arthritis. Such risks include those associated with the transplantation procedure itself, anesthesia, possible ineffectiveness, converting from pain-free to painful status, and the real risk of exposure to disease transmission with allograft tissue. Until long-term effectiveness is established in these “at-risk” patients, transplantation should not be performed prophylactically.

Contraindications

Contraindications to meniscus transplantation include patients whose symptoms are not the result of meniscus insufficiency. For example, pain should be localized in the meniscal-deficient compartment. This requires careful clinical assessment preoperatively. In equivocal cases, we have found temporary (3 days) use of a short leg cast with a wedge to unload the affected compartment a helpful clinical tool.

The most common contraindication is the presence of significant chondral pathology in the affected compartment. Studies have shown a clear relationship
between the status of the articular surfaces and outcome. Outerbridge changes greater than grade III (significant partial-thickness lesions) probably precludes implantation. Certainly, grade IV lesions, in which subchondral bone is exposed, is considered a hostile environment and risks the transplant’s survival. As alternative articular cartilage restoration techniques evolve, some surgeons have found that articular resurfacing for focal grade III and IV lesions could permit meniscus transplantation simultaneously or in a staged procedure. However, these lesions must be geographic and contained with good “shoulders.” Other contraindications include patients whose alignment is uncorrected or uncorrectable, whose instability is uncorrectable, and those patients who have unrealistic expectations or are unwilling to modify their activities postoperatively. Weight, age, and a history of previous infections are all relative contraindications.

Preoperative Considerations

Preoperative decisions involve selection of the appropriate meniscus allograft. There is little current standardization, and tissue banks differ in a number of ways, including donor screening and procurement methods, specimen testing, tissue processing, storage, size of inventory, and sizing technique.

Donor Screening, Procurement, and Testing

Tissue banks are similar in terms of donor screening, procurement, and testing. Most tissue is harvested using a “sterile technique.” The donor and family are carefully screened with respect to medical, social, and sexual history. Postmortem harvested tissue samples are tested for a number of diseases, including HIV-1 and HIV-2 antibody, hepatitis B surface antigen, hepatitis C antibody, syphilis, human T-cell lymphotropic virus antibody, and aerobic and anaerobic infection. Tissues are then quarantined and released only if/when tests are negative.

Although tissue procurement is purportedly under “sterile” conditions, there remain risks of infection through technique and potential delay from procurement to refrigeration. For this reason, “secondary” processing is routinely carried out to further minimize infection risk. Historically, chemical processing with ethylene oxide was thought effective but has since been abandoned as a result of the synovitis caused by its breakdown products. Current techniques include antibiotic soaks, detergent wash/rinses, and, in some banks, “pretreatment” with low-dose irradiation. This pretreatment radiation strategy is intended to reduce surface bacterial contamination. However, use of radiation is somewhat limited, because the amount required to inactivate viral load exceeds the mechanical integrity of the graft tissue. Therefore, other than superficial bacterial eradication, “pretreatment” does not in fact substantially reduce the risk of disease transmission. Specifically, the amount of radiation thought necessary to effectively eradicate viral risk is 3 megarads. Graft integrity becomes compromised at approximately 2.5 megarads. Notwithstanding processing efforts, there remains no current absolutely reliable method to ensure tissue safety.

In light of problems with bacterial contamination and infection leading to the death of a young patient after osteochondral allograft implantation, the Centers for Disease Control and Prevention has made specific recommendations for tissue bank safety, which are available on their website. They recommend that tissue should be cultured before suspension in an antibiotic solution, and if a Clostridium species is identified, all the donor tissue that cannot be sterilized should be discarded. Secondly, unless a sporicidal method is used, aseptically processed tissue should not be considered sterile, and all healthcare providers should be informed of the possible risk of bacterial infection.

Other infection risks include hepatitis C and HIV, with one reported case of HIV transmission involving a frozen unsterilized graft. HIV has been cultured from both cryopreserved and freeze-dried specimens. This underscores the fact that procurement methods cannot be counted on to completely eliminate the risk. The risk of HIV transmission has been evaluated and reported as one in 1.6 million. In addition, there is a 6- to 12-day “window” from exposure of HIV until seroconversion, indicating yet another possibility of undetected disease transmission. The window of opportunity can be narrowed, but it cannot, at least currently, be entirely eliminated.

Tissue Processing/Storage

Tissue banks differ in the method by which tissue is processed. The four main processing methods include freeze-drying, fresh, fresh-frozen, and cryopreserved. Freeze-dried allografts are frozen in a vacuum environment with removal of water (lyophilization). Advantages include its indefinite storage and its relative low cost. Disadvantages include the fact that it is unpredictable when it is rehydrated with respect to size, it is brittle to handle, and it is nearly completely
resorbed in trials. For this reason, it has been all but abandoned clinically.

Fresh allograft is implanted within several days of harvesting after being placed in lactated Ringer’s solution and stored at 2° to 4°C for up to 7 days. Advantages include the fact that it is thought to preserve cell viability, enhance basement membrane preservation, and therefore improve outcome. Disadvantages include the fact that DNA studies have demonstrated that the graft is subsequently repopulated after implantation by the recipient cells, thereby invalidating the benefit of donor cell preservation. Furthermore, fresh tissue is limited in availability and presents logistic difficulties. Fresh-frozen allograft includes harvesting and freezing tissue at -80°C for up to 3 to 5 years. Advantages include the fact that it is easily and inexpensively processed, and despite theoretical concern about cell death, clinical results with this tissue are quite good. Disadvantages include the fact that it has been, at least until recently, somewhat limited in availability, but it appears to be a good option when available.

Cryopreserved allograft is tissue that is frozen under very specific conditions using dimethyl sulfoxide preservative. Theoretic advantages include its preservation of cell membrane integrity and cellular viability, although it is estimated that only approximately 30% of cells remain viable. Disadvantages include its cost, the fact that it has not been proven superior to fresh-frozen tissue, and the fact that it is currently limited in availability.

Sizing Methods

Currently, there is no standardized protocol for sizing the meniscus, and most transplant surgeons rely on the tissue bank to do this job. Current banking protocols all rely on the use of standard x-rays to estimate the meniscus dimensions. The negative experience with mismatch led to the examination of alternative methods for meniscus sizing, including evaluation of MRI and computed tomography (CT) in comparison to conventional films. MRI was found to be surprisingly inaccurate in estimating meniscal dimensions. In a subsequent unpublished study, CT scan has been found to be highly accurate in assessing bone dimensions in both coronal and sagittal planes, and is more accurate than x-rays (Shaffer B, personal communication, 2000).

A current preferred protocol involves obtaining a preoperative CT with axial cuts beginning at the intercondylar eminence and progressing distally until the subchondral bone of the affected compartment is clearly delineated. On this cut, the anteroposterior (AP) length of the bone dimension is directly measured. Using a conventional AP radiograph with a ruler, meniscus medial-lateral “width” is measured from the periphery of the affected compartment to the nearest intercondylar eminence. This combination of measurement allows a more predictable determination of the appropriate bone dimensions of the graft.

Surgical Technique

The surgical technique has evolved from implantation using arthrotomy to the current arthroscopic-assisted technique. Several methods have been developed for transplant but have evolved into a “plug” technique for medial grafts and a “trench” technique laterally. In both techniques, the surgery begins with arthroscopic examination and debridement of remnant posterior meniscus. Historically, arthroscopic examination permitted assessment of chondral surfaces, and the graft would not be opened until satisfactory chondral surfaces were confirmed first. Currently, banks do not permit return of the grafts. This policy has resulted in carrying out the arthroscopic examination first before the definitive second-stage implantation in the vast majority of cases. This ensures that the grafts are not wasted unnecessarily. In addition, the cost can be somewhat prohibitive if the graft is unused, approaching $5,000 in most banks. Unfortunately, the patient must undergo the expense, inconvenience, and risk of an additional procedure, but the minimal risks associated with diagnostic arthroscopy and the ability to avoid unnecessary waste of unused tissue is probably a reasonable trade-off.

The mid- and posterior body meniscal remnant is resected and the peripheral meniscosynovial junction abraded to generate a healing response. Care must be taken not to remove too much tissue peripherally, because apposition of the peripheral tissue to the transplant is critical to successful healing. Rim preparation is performed as would be carried out in a meniscal repair to stimulate healing. The anterior meniscus horn and body are left intact, because they are easily removed through the small anterior arthrotomy to be performed for graft passage. At this time, the two techniques diverge, based on which compartment is being transplanted.

Medial Meniscus Transplantation

In carrying out a medial meniscal transplant, the next step includes drilling of a posterior tibial tunnel.
This requires familiarity with normal insertion sites and adequate visualization, which, on occasion, requires the use of a posteromedial portal or use of a 70° scope. An ACL guide is used through the ipsilateral portal to establish the posterior tibial tunnel, which is usually 7 mm in diameter. The graft is prepared on the back table to trim excess soft tissues and outline the plugs, and the sagittal saw is used to make the plugs. A coring reamer can be used as well and/or a burr to pare down the plugs. The posterior plug is undersized to a 6-mm diameter so that it will easily fit into the 7-mm tunnel. The plug is also trimmed so that it is no longer than 6 to 7 mm in length. The anterior plug, which will be press-fit, is a 10-mm diameter plug and can be 8 to 10 mm in length. No. 1 nonabsorbable sutures are passed through the anterior and posterior horn, respectively, and, using a straight needle, are passed through the central portion of the bone plugs.

An inside-out suture technique for the peripheral repair is preferred and so a posteromedial incision is carried out, developing the plane between the posteromedial capsule and the gastrocnemius, avoiding the infrapatellar branch of the saphenous nerve. At this time, a small anteromedial arthrotomy is carried out, usually under tourniquet. The remaining anterior meniscus body is resected and the graft is subsequently passed from anterior to posterior with a guide suture placed at the posteromedial periphery of the meniscus to maintain orientation of the graft during placement. The meniscus is pulled into place and secured. Passage of the meniscus is the most difficult part of this case, and alternative techniques for facilitating this include “pickling” the medial collateral ligament (MCL) with the use of a No. 11 blade through the ipsilateral scope portal. Several small horizontal “nicks” in the deep capsule of the MCL followed by gentle valgus stress will yield a little more opening that often permits easier graft passage. Other “tricks” include downsizing the posterior plug, making its passage easier. Removal of some of the eminence (with a shaver or burr), and performing a small notchplasty on the inner aspect of the medial femoral condyle, will also facilitate passage. On rare occasions, the graft might need to be passed from posterior to anterior through a small posteromedial arthrotomy. It is important to avoid compromising on use of bone plugs for fixation, because they are critical to prevent graft extrusion and improper loading and the biomechanical importance of bone plug preservation has been shown in several studies.

After graft passage, the anterior tunnel is drilled from outside-in. It is easier to establish the tunnel after graft passage and seating to ensure the horn attachment respects the manner in which the meniscus sits in the knee. The knee tunnels ought to be modified to fit the meniscus, not the other way around. The anterior mini-arthrotomy is closed and an inside-out repair technique is performed using 2-0 nonabsorbable sutures. The meniscus is then repaired using an inside-out technique with double-armed meniscal repair sutures. Repair of the anterior meniscus is performed under direct visualization. A small tag of tissue on the anterior horn is usually repaired to the intermeniscal ligament remnant.

Lateral Meniscal Transplantation

Although bone plugs can be used in performing a lateral meniscal transplant, horn proximity of approximately 1 cm risks potential tunnel coalescence and breakthrough. For this reason, alternative techniques, including the use of a bridge, a keyhole, and most recently a trough, have been developed. The trough technique, with relatively simplified instrumentation, makes this approach relatively easy. Having confirmed the appropriateness of the transplant, a trough is started, aiming from the anterior to the posterior horn of the lateral meniscus. This line of site must be collinear with the meniscal horns. On completion of the arthroscopy, a small anterolateral arthrotomy is made in line with the previous portal, which is initially made vertical so that it can be incorporated at this point. Some of the infrapatellar fat pad is often removed for improved visualization and the remnant anterior meniscus body resected. The intermeniscal ligament is preserved for later reattachment. A series of small chisels is effective in gradually enlarging the trough until the predetermined diameter (varying from 7-10 mm) is achieved. Care is taken to ensure the trough is collinear with the horn attachment sites. Because of the overlying patellar tendon, such easy targeting is often not achievable and forces one to lateralize the trough nonanatomically. Another useful technique includes splitting the patellar tendon to permit easier direct targeting and establishment of the lateral trough. This has permitted a far easier approach to a perfect anatomic shot in comparison to struggling with retracting the tendon medially. After ensuring adequate trough width and length, the graft is trimmed on the back table to ensure a good press-fit. The graft is seated carefully in place under gentle varus stress and usually is much easier in comparison to medial passage. A posterolateral incision (under tourniquet control) permits suture retrieval during subsequent
meniscal repair using an inside-out technique. Although sutures can be placed in the bone block for additional fixation (using two ACL-guided drill holes into the base of the trough), we have not found this accessory fixation necessary when the graft has been properly press-fit. After graft seating, for both medial and lateral transplants, the knee is cycled through a range of motion to ensure adequate positioning.

Postoperative Rehabilitation

The postoperative rehabilitation protocol is similar for both approaches, with nonweight-bearing for the first 2 weeks, and then progressive weight-bearing until full weight-bearing at 6 weeks. Continuous passive motion is used for the first 3 weeks to restore mobility and control swelling. Running, squatting, pivoting, and twisting are avoided until minimum 5 and usually closer to 6 months after surgery.

Outcome

Milachowski was the first to perform a human meniscus transplant and reported in 1989 on his early results with 22 patients at 14 months follow up. All underwent a simultaneous ACL reconstruction with an overall 85% success rate. Second-look follow up in 3 years, examination showed meniscal shrinkage, which he attributed to the freeze-drying process.

Follow-up studies in the United States demonstrated overall good to excellent results in a high percentage of patients. Most underwent transplants in association with some other concomitant procedure. Second-look arthroscopy in a number of these showed a small number that underwent shrinkage and a high percentage that went on to peripheral healing. Failure rates were attributed to the presence of arthritis. At intermediate follow up, from 30 to 40 months, several subsequent studies reaffirmed the good early results. Harner demonstrated degenerative changes in all lateral meniscal transplants (Harner C, personal communication, 1997). In a recent publication, Stolsteimer showed that graft size was only 63% of normal in 12 of 22 transplants and noted that "shrinkage in size of meniscus as shown on MRI is a concern."89

Longer follow-up studies have continued to show good results, but also suggested a note of caution. Rath demonstrated that 36% of their menisci at 5.4 years were torn, necessitating six partial and two total meniscectomies.90 Shaffer has experience with 28 transplants, 16 of which were isolated and 10 combined with ACL; and in 2 with an ACL/posterior cruciate ligament, 71% of patients have done well with few or no symptoms.91 Five patients required further surgery, with one graft removed as a result of placement in an arthritic joint, one removed as a result of infection unresponsive to multiple debridements, one removed as a result of flexion contracture when the graft was incompletely seated. Two patients subsequently required meniscectomy, one partial as a result of an oblique tear at 4 years postimplantation, and the other a subtotal meniscectomy as a result of an irreparable bucket-handle tear of the entire transplant at 5 years postoperatively. One patient continues to do well 3 years after surgery, despite malpositioning within the joint.

In summary, good to excellent overall results are present in most series, but scrutiny of these studies show considerable variability in indications, type of graft, surgical technique, presence of concomitant surgery, duration of follow up, and criteria for success.

Does Meniscus Transplantation Work?

We know (from widespread experience and second-look arthroscopy) that the grafts heal, become revascularized, are repopulated by the recipient cells, and usually look normal at second-look arthroscopy and close to normal by MRI criteria.92 However, there are no tests to indicate whether the graft will, in fact, provide the intended stress protection to articular cartilage over the long term.

In sheep models, meniscus transplantation has been shown to have a protective effect against articular degeneration, but we have not yet been able to demonstrate that this protective benefit will accrue to the patients in whom we are transplanting menisci. We have a current dilemma in meniscus transplantation. The patient who is most interested in the meniscus transplant, i.e., the symptomatic meniscal-deficient patient, is probably the least appropriate candidate because of already pre-existent chondral and degenerative pathology. Ironically, it is the patient with the fewest (or no) symptoms in whom we could have the best chance to preserve chondral integrity over time but the least justification to recommend it. Until such proof of the meniscus transplants’ protective benefit, prophylactic implantation is probably inappropriate for most patients.

Complications

Complications are few and uncommonly reported, but include meniscus retears, graft shrinkage, mechanical symptoms, loss of fixation, hemarthrosis, synovitis, recurrent effusion, stiffness, arthrofibrosis, infec-
tion, and one case report of an immune or rejection response. Disease transmission has not (yet) been reported. Although not a complication per se, progressive chondral changes toward degenerative arthritis remains an obvious concern.

**MENISCUS TRANSPLANTATION CONCLUSIONS**

In conclusion, the meniscus is critical to normal knee function. Surgical efforts have evolved from meniscus preservation to replacement. Basic science studies suggest that transplants could well protect articular cartilage, and allograft transplantation has certainly proven clinically effective in the short-to-intermediate term. However, longer clinical follow up will determine its true value. Biomechanical studies are needed to optimize graft selection and sizing. Hopefully, parallel research into the development of alternative meniscal substitutes will provide low-risk alternatives.

**FUTURE DIRECTIONS IN MENISCAL SURGERY**

**Biomechanics of the Meniscus**

The human knee joint is a complex biomechanical system with the menisci as an integral component. Kinematic behavior of the menisci was described by Thompson and coauthors who used cadaveric specimens and three-dimensional reconstruction MRI. During flexion, the posterior excursion of the medial meniscus was described as 5.1 mm, and of the lateral meniscus as 11.2 mm. The anterior horn segments were thereby shown to be more mobile than the posterior horn segments bilaterally (Fig 10). Meniscal kinematics have also been described after allograft reconstruction by Johnson and coworkers and were found to be much smaller. During flexion, the posterior excursion of the medial meniscus transplant, at an average of 15-month follow up, was described as 2.6 mm, and of the lateral meniscus transplant as 3.6 mm.

The insertion site geometry of the menisci was previously described (Fig 11). The insertions of the anterior and posterior horns are found in very close proximity to the cruciate ligament insertions. When the knee is loaded during compression, the concave surface of the menisci experiences a vertical force and a radially directed component that tends to displace the menisci outward. The strong insertion site attachments restrain this displacement and give rise to a large component of circumferentially directed force and associated hoop stresses within the meniscal substance.

Allen and coworkers investigated the importance of the medial meniscus in the ACL-deficient knee. In this study, it was found that the force in the medial meniscus of the ACL-deficient knee increased by 52% to 197%, depending on the knee flexion angle, when compared with the force in the meniscus of the intact knee. Further studies investigated the biomechanical interdependence between an ACL replacement graft and the medial meniscus. Forces in the ACL replacement graft increased between 33% and 50% after medial meniscectomy.

**Stem Cells**

Stem cells have the capacity for multipotential differentiation and therefore have become attractive for clinical applications such as cell-based therapy and tissue engineering. An experimental study of rabbit menisci was carried out to evaluate the healing potential of fibrin glue and fibrin glue-containing marrow cells. The results suggest that fibrin glue, especially in a preparation containing marrow cells, can enhance meniscal healing. Caplan and colleagues investigated meniscus repair using a type I collagen sponge loaded with autologous, bone marrow-derived, cultured mesenchymal stem cells. They have shown that the cultured mesenchymal stem cells could enhance the repair process in some specimens to produce fibrocartilage that was histologically similar to normal meniscus. Stem cells were reported to proliferate for an extended period of time and display a strong capacity for self-renewal.

**Scaffolds**

In meniscus repair, periosteal and perichondral flaps, as well as small intestinal submucosa (SIS), have been used. SIS has been used to repair musculoskeletal tissues and has been shown to promote cell migration into the healing site to enhance revascularization and repair. When used to repair meniscal defects with SIS, the histomorphologic appearance of the tissue more closely resembled uninjured tissue than nontreated menisci. Scaffolding materials such as synthetic polymers including polyglycolic acid (PGA), polylactic acid (PLA), polylactic-co-glycolic acid (PLGA), calcium phosphate ceramics, alginate, and hyaluronate have been used for meniscus replacement and, after seeding with
meniscus cells\textsuperscript{121,122} or mesenchymal stem cells,\textsuperscript{113} used as a scaffolding material to repair or replace injured menisci.

**Future Treatments**

Tissue repair and regeneration is a complex and multicomponent process. Several tools are available and their combination seems most appropriate. The components are gene therapy, stem cell therapy, and tissue engineering (Fig 12). Furthermore, interdisciplinary collaboration between molecular biologist, material scientists, biomechanical engineers, and orthopaedic surgeons will be crucial for the future success of these technologies. Before clinical applicability of these tools, a number of basic science and randomized, controlled clinical trials have to be conducted. However, at present, surgeons are using various simple techniques to biologically enhance meniscus repair. For example, neovascularization techniques applied around a meniscal tear or techniques such as synovial abrasion and meniscal trephination have been described,\textsuperscript{123,124} In a goat model, it was
shown that vascular access channels can allow proliferation of fibrous vascular scar tissue from the vascular channel into the tear site.\textsuperscript{125}

Growth factors are proteins, which can be liberated by cells at the injury site (e.g., fibroblasts, endothelial cells, muscle cells, mesenchymal stem cells) and by the infiltrating reparatory or inflammatory cells (e.g., platelets, macrophages). They are capable of stimulating cells toward proliferation, migration, matrix synthesis, and differentiation.\textsuperscript{126-131} The direct application of human recombinant therapeutic proteins can enhance the healing process; however, this application is limited by a short biologic half-life, and the need for repeated and high dosages of growth factors. DNA that encodes for a specific protein can also be delivered into a target cell so that the cell starts expressing the growth factor on its own. The most commonly used method of gene delivery is a viral insertion of the DNA into the target cell.\textsuperscript{132-134} The transferred gene is either integrated into the chromosomal DNA (e.g., retroviral transfection) or maintained separately in the cell as an episome (e.g., adenoviral transfection).\textsuperscript{135} For expression, the desired gene has to enter the pathways of transcription (copying the DNA into mRNA), translation (actual protein synthesis according to the mRNA template), and secretion of the therapeutic protein (e.g., growth factor). This process can be repeated so that the genetically manipulated cells serve as a reservoir for growth factors improving healing (Fig 13).

**Gene Therapy**

Gene therapy was originally for the manipulation of germ-line cells for treating inherited genetic disorders, but this application has been limited as a result of considerable ethical concern. Conversely, the manipulation of somatic cells has been widely accepted. However, the recently reported cases on development of leukemia-like side effects of clinical trials for the treatment of children with severe combined immunodeficiency (SCID) have raised concerns about the risk benefit ratio of gene therapy. Thus, research addressing safety issues is invaluable, especially in the field of orthopaedic sports medicine, where elective surgeries are performed on a relatively young population.\textsuperscript{136}

Strategies for local gene therapy have been extensively investigated. Vectors can be directly injected in the host tissue, or cells in culture can be genetically altered ex vivo and then transplanted.\textsuperscript{137} Although the direct method is technically easier to achieve, the cell based ex vivo approach bares less risk, because gene manipulation occurs outside the body of the host. Furthermore, the genetically engineered and trans-
planted cells supply the host with the desired gene and with cells participating in the healing process. Decreased gene expression over time is common and its mechanisms are not fully understood. However, in certain tissues such as articular discs of the spine, gene expression could be observed in rabbits for more than 12 months. Currently, research is focusing on regulating gene expression. Specifically, the induction of gene expression could help to control and modulate implanted genes while turning them on and off.

Goto and coworkers showed that retroviral gene transfer to a meniscal injury site is possible and that genes can be expressed locally within the injury site for several weeks (Fig 14). The implications of this study are that healing of the avascular portion of the meniscus can be improved by the transfer of genes that encode for growth factors such as PDGF, IGF-1, or hyaluronan. To investigate the feasibility of gene transfer in meniscal allografts, Martinek and coworkers performed meniscus replacements with ex vivo retrovirally transduced meniscal allografts, and the expression of a lacZ marker gene was determined in a rabbit model. Gene expression in the superficial cell layers of the menisci persisted and the transduced cells were found at the menisco-synovial junction of the transplants and in deeper layers of the menisci. Future investigations will use vectors expressing therapeutic growth factors to assess their potential to

**Figure 13.** Schematic drawing of gene therapy using a viral vector. (Reprinted with permission.)

**Figure 14.** Radial section of a canine meniscus after retrovirally mediated ex-vivo gene transfer to a surgically created meniscal defect. Two weeks after gene transfer, a large number of lacZ+ cells can be seen in the defect (×200). (Reprinted with permission.)
improve remodeling and healing of meniscal allografts (Fig 15). 144

**Functional Tissue Engineering**

Although gene therapy is not yet established as a clinical therapy, it has great potential for the treatment of musculoskeletal injuries in the future. Recently, phase I of the first clinical trial in orthopaedics was successfully completed for human joints. 137,145 It is believed that further tissue engineering with muscle-derived stem cells and gene therapy will lead to the development of new treatment strategies for tissues with low healing capacities such as meniscal tissue. New techniques, which address the biologic base of healing, might further improve the outcome and create indications for surgical interventions in tissues with low healing potential. However, a large number of basic science studies and preclinical trials have to be completed to reach the necessary efficiency and safety for orthopaedic sports medicine applications.

The future of meniscus surgery will be based on designing a tissue-engineered meniscus. This process requires consideration of specific biologic factors such as type of cell and matrix, and environmental conditions. In experimental studies, meniscal cells, fibroblasts, and mesenchymal stem cells have been used as cell sources and have been grown on various cell matrices, including collagen-based scaffolds, biodegradable polymers, or SIS. 113,117,119,121

Stem cells are cells that can turn into different tissue types such as bone, cartilage, muscle, or tendon. For example, fetal umbilical cord cells are stem cells that display the ability to differentiate in various tissue types. Unfortunately, they are not available in adults. In contrast, bone marrow-derived stem cells and muscle-derived stem cells persist throughout life, are available in abundance, and easily accessible through a biopsy. A special stem cell population derived from muscle tissue was identified, and tissue engineering approaches are currently under development; that means biologic substitutes for repair, reconstruction, regeneration, or replacement of musculoskeletal tissues with muscle-derived stem cells. 146

Functional tissue engineering is a novel approach to...
enhance tissue regeneration and provides the possibility of producing tissue that is biomechanically, biochemically, and histomorphologically similar to the normal. The basic concept of tissue engineering is based on the manipulation of cellular and biochemical mediators to affect protein synthesis and to improve tissue formation and remodeling. Ultimately, the process is expected to lead to a restoration of mechanical properties. The available approaches include, for example, the use of growth factors, gene transfer technology to deliver genetic material, stem cell therapy, and the use of scaffolding as well as external mechanical factors. Each of these approaches, or their combinations, offers the opportunity to enhance the healing process.

CONCLUSIONS

Advances in regenerative medicine, cell biology, genomics, and biomaterials hold promise for development of effective treatment techniques for meniscal injuries. Although numerous basic science research studies are on their way, less than 5% of these studies will make their way into clinical practice in the near future. Treating meniscus injuries and athletes with early arthritis will most likely remain a clinical challenge. The objective should be to save the meniscus whenever possible and refrain from substantial meniscus resections. Meniscal restoration can be expected through comprehensive assessment, further elucidation of cell biology, and functional tissue engineering.

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