Meniscal repair and replacement

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Abstract

Viewed for many years as just vestigial organs, a lack of appreciation of the importance of the menisci led to the widespread practice of total meniscectomy. The realization that removal of these important structures leads to accelerated arthritis took some time. It is now recognized that the menisci play an important role in load distribution, joint stability and lubrication, protecting the joint surfaces from degenerative change. As awareness of the true importance of these important structures has increased, and so has the understanding of different patterns of meniscal injury and the interaction of additional factors, such as alignment and ligamentous stability, in determining long-term meniscal and knee function. This has led to an integrated approach to meniscal surgery as part of an overall strategy to preserve and restore knee function, incorporating a shift towards meniscal preserving surgery whenever possible. This article will review knee anatomy and biomechanics as a basis for understanding the mechanism and classification of meniscal tears and associated injuries. Assessment, surgical decision-making and repair techniques, including the role of biological augmentation to increase the scope of repairable injuries, will also be reviewed. Options to reconstruct the meniscus using meniscal allograft transplantation for patients with symptomatic meniscal deficiency will be discussed.

Keywords bucket-handle tear; knee; meniscal repair; meniscal root-tear; meniscus; meniscus transplantation

Introduction

Meniscal tears are common, with a yearly incidence of 35–61 per 100,000 population. Due to its effectiveness at resolving mechanical symptoms and rapidly restoring normal function and gait in the acutely locked knee, partial meniscectomy has become established as one of the most commonly performed operations in knee surgery. The procedure can allow a rapid return to activities; however, loss of meniscal tissue predisposes the knee joint to degenerative change and symptoms over a variable length of time. Repair is an important option for meniscal tears, reducing the risk of subsequent arthritis, but the factors in favour of repair *versus* meniscectomy require clarification. If deficient, then reconstruction by meniscal transplantation is a clinically effective solution for symptomatic knees. This paper reviews contemporary opinions regarding meniscal repair and meniscal reconstruction by meniscal allograft transplantation.

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Meniscal anatomy and function

Consequences of meniscal deficiency

Although effective in the short-term, long-term follow-up of meniscal deficient patients after partial or total meniscectomy has demonstrated increased risk of osteoarthritis (OA). In a systematic review of the risk factors for OA, Papalia et al. reported a 7-times increase in the radiological diagnosis of OA at 5- to 30-year follow-up after the surgical management of meniscal tears (40% in the operated vs 6% in the contralateral/control knee), with a higher incidence following lateral compared to medial, and with total compared to partial-meniscectomy.[1] In a single cohort follow-up study of adolescents who underwent total meniscectomy at a mean age of 16, Pengas et al. reported a 132-fold increase in the incidence of knee arthroplasty at a mean of 40 years follow-up compared with geographic and age-matched controls.[2]

Meniscal function

Menisci are found in all mammals, and their primary role is to improve congruency between the convex surface of the distal femur and the surfaces of the proximal tibia. This helps distribute load evenly across the knee throughout the range of motion, thereby decreasing the resultant stress experienced by articular cartilage. The menisci are not so much 'shock absorbers', but rather 'load distributors'. The menisci are also important stabilizers of the knee joint, which is particularly important in anterior cruciate ligament (ACL) reconstruction, where higher failure rates have been reported with meniscal deficiency. In addition, the menisci also contribute to proprioception, cartilage nutrition and lubrication.

Anatomy

The anatomy of the menisci is illustrated in Figure 1. The menisci are cartilaginous structures with a triangular cross-section, located between the femoral condyles and the tibial plateau in the knee. The anterior and posterior horns of the menisci are stabilized by strong ligamentous root attachments to the tibial intercondylar region.

The medial meniscus is a slightly asymmetrical C-shaped shaped structure, having a larger posterior than anterior horn. According to Bloecker et al., who assessed meniscal size on MRI images, the medial meniscus covers 50% ±6% of the medial plateau, and it is firmly attached to the periphery via the deep medial collateral ligament, which has both menisco-femoral and menisco-tibial attachments.[3] Hence, the medial meniscus is relatively immobile, with only about 5 mm of anterior-posterior translation during knee flexion and extension.[4] The larger posterior third comes under most load in deep flexion.

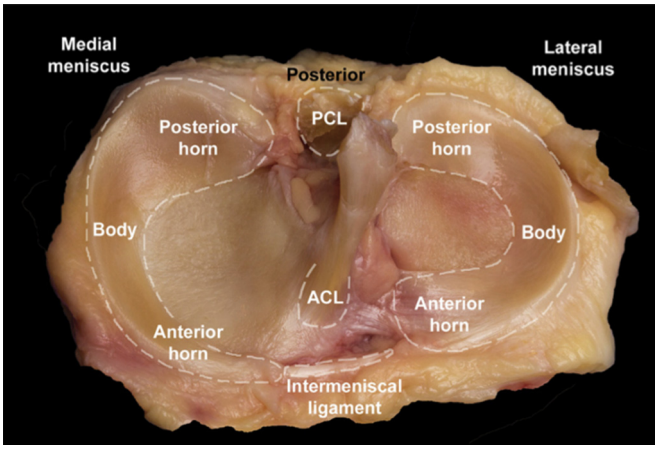

Figure 1 Superior view of a cadaveric left tibial plateau showing meniscal anatomy and attachments. The C-shaped medial meniscus covers around 50% of the medial tibial plateau. It has capsular attachments to the femur and tibia via the deep medial collateral ligament (MCL), to the tibia anterior to the anterior cruciate ligament (ACL) to the tibia via the coronary ligament and to the lateral meniscus via the intermeniscal ligament. These attachments limit movement to around 4 mm anteroposterior translation during flexion and extension. In contrast, the lateral meniscus is more semicircular and covers around 60% of the tibial articular surface. The anterior horn is attached to the intermeniscal ligament and to the tibial eminence just posterior to the insertion of the ACL. The posterior horn is attached to the tibia in the intercondylar region and to the medial femoral condyle via the ligaments of Humphrey, anterior to the posterior cruciate ligament (PCL), and Wrisberg, posterior to the posterior cruciate ligament. Source: reproduced from reference[25] with permission of Mayo Foundation for Medical Education and Research. Mayo 2017. All rights reserved.

The lateral meniscus is more symmetrical, forming almost a complete circle shape. It is similar in volume to the medial meniscus, but covers a relatively larger proportion of the lateral tibial plateau, quantified as 59% ±7%.[3] It is less firmly attached to the periphery, and more mobile, with approximately 11 mm posterior translation during knee flexion as the lateral condyle rolls posteriorly.[4]

Ultrastructure and biology

The menisci are composed of an interlacing network of collagen fibres, proteoglycans and glycoproteins, and are approximately 75% water, 20% Type I collagen and 5% other substances, including proteoglycans, elastin, Type II collagen and fibrochondrocytes. The properties of the various regions of the meniscus are determined by the composition and microstructure of the tissue, which transitions from highly aligned longitudinally orientated collagenous fibres, closely resembling a ligamentous structure in the outer rim, to a woven less aligned structure in the inner meniscus, more closely resembling hyaline cartilage. The predominantly circumferential arrangement of the collagen fibres is vital to meniscal function. As the knee is loaded, joint compression acts to extrude the menisci in a radial direction towards the periphery of the joint. 'Hoop stress' in the circumferential fibres resists this extrusion, which helps dissipate axial loads and which protects the adjacent hyaline cartilage.[5]

Resistance to hoop stresses relies on the firm attachment of the menisci to the tibial plateau. The anterior and posterior roots, the anterior intermeniscal ligament, the medial collateral ligament, the menisco-femoral ligaments and the coronary ligaments all aid in meniscal stability, with the root attachments and anterior intermeniscal ligament resisting hoop stresses during loading.

Biomechanics

Knee flexion-extension occurs via a glide-roll mechanism, rather than pure pivoting, with the anterior-posterior translation of the central pivot controlled by a combination of underlying bony anatomy, the cruciate ligaments, the menisci and capsular structures. As the knee moves into full extension, external rotation of the tibia with respect to the femur occurs via the so-called 'screw home' mechanism. At full extension the femur has a large contact area, with the tibial plateaus pressing anteriorly on the meniscal horns. As the knee flexes, tibial internal rotation occurs (the reverse of the screw home) and contact moves posteriorly towards the posterior meniscal horns due to femoral 'roll-back'. The contact area with the tibial plateau is thus reduced as the lesser radii of curvature of the posterior femoral condyles sequentially come into contact. The medial tibial plateau is slightly concave and is made more concave by the meniscus, while the lateral tibial plateau is flat or slightly convex. As a result, the centre of contact on the medial side remains relatively constant, in terms of antero-posterior position, whilst the lateral condyle rolls posteriorly towards the posterior horn of the mobile lateral meniscus; thus, tibial rotation occurs mainly about a medial axis, with the centre of rotation medial to the knee joint in the axial plane (Figure 2).[6]

During this complex motion, approximately 50% of the compressive load is transmitted through the menisci as the knee goes into extension, while meniscal load can increase to as much as 85% in flexion.[5] The medial meniscus bears about 50% of load through the medial compartment whereas the lateral meniscus bears up to 70% of the lateral load.[7] Without a meniscus the tibio-femoral contact area is reduced by 50–75% and the peak contact pressure is increased by 200–300%.[8]

Vascularity

Meniscal blood supply is crucial to the chances of a repair healing successfully. Arising from the superior and inferior medial and lateral genicular arteries, and provided through the perimeniscal capillary plexus in the capsular and synovial tissues, the lateral meniscus is vascularized in only the outer 10–25% of its width and the medial meniscus in the outer 10–30% in adults.[9] At birth the width of the vascular margin is higher (up to 50% of the width) but this slowly declines to the adult state by age 12. Hence, the chances of healing are highest in the well-vascularized peripheral third of the meniscus in adults and potentially the outer two-thirds of the meniscus in younger children (Figure 3).

Assessment and classification of meniscal tears

Several systems for classifying meniscal tears have been proposed, based on vascularity (healing potential), size, depth and location of the tear, morphology and orientation (with respect to the meniscal collagen fibres) and associated stability of the knee. These classifications are summarized in Figures 4 and 5.

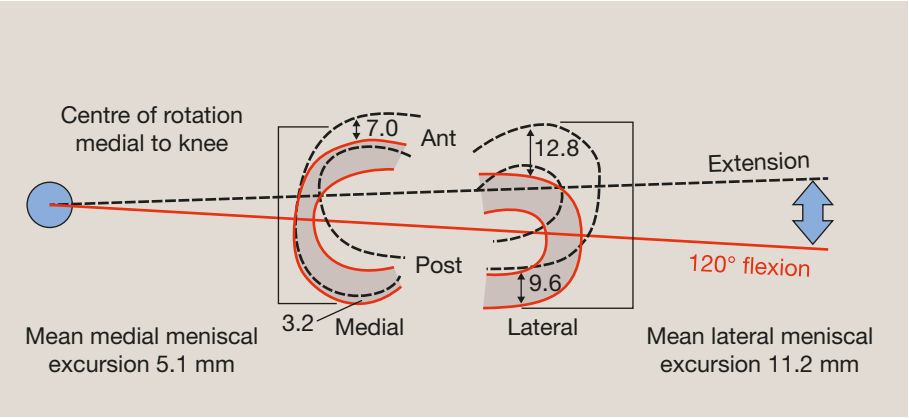

Figure 2 Diagram of meniscal excursion.[4] Mean meniscal excursion from anterior (Ant) to posterior (Post) is shown as the knee moves from extension (meniscal position in extension shown by black dotted line) to 120° flexion (meniscal position in 120° flexion shown by red line and shaded meniscus). The mean lateral meniscal excursion is greater than the mean medial meniscal excursion (11.2 mm vs 5.1 mm), such that in the axial plane the centre of rotation of the knee lies medial to the knee joint. Relative tibial internal rotation and femoral external rotation occur with flexion. The inverse motion of relative tibial external rotation and femoral internal rotation occur as the knee moves into extension, referred to as the 'screw home mechanism'.

The European Society of Sports Trauma, Knee Surgery and Arthroscopy/International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ESSKA/ISAKOS) Classification (2006) is based on tear depth (full/partial thickness); residual rim width (<3 mm, 3–5 mm, >5 mm); and location (posterior, mid-body, anterior). Residual rim width is a proxy for meniscal function, as lesions with less than 3 mm of rim remaining compromise the circumferential fibres and the ability of the meniscus to resist hoop stress, effectively defunctioning the meniscus.

Vascularity and location

Classification of tears based on vascularity has been validated in both animal models and clinical studies. Based on anatomical vascular studies, Arnoczky and Warren divided the meniscus into three radial zones: 'red-red' peripherally, 'red-white' as an intermediate zone, and white–white centrally.[9] 'Red-red' tears in the peripheral vascularized area (0–3 mm from the rim) have the best chance of healing, with a tear location within 0–2 mm of the menisco-capsular junction having the greatest overall capacity for healing. 'White–white' tears in the inner avascular zone (5–7 mm from the rim in adults and children over 12) have the lowest healing potential. Tears in the intermediate zone (3–5 mm from the rim) in adults and the 'central zone' in younger children (as up to age of 12 the intermediate zone may remain vascularized), termed 'red-white', have intermediate potential for healing, depending on age. The classification was subsequently modified to further subdivide the menisci into three segments from anterior to posterior (anterior horn, body and posterior horn).[10]

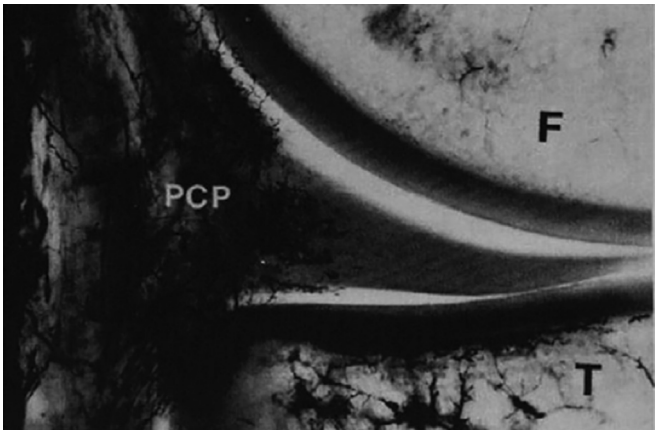

Figure 3 Microvasculature of the medial meniscus following vascular perfusion with India ink and tissue clearing, using a modified Spalteholz technique. The perimeniscal capillary plexus (PCP) can be seen penetrating the peripheral border of the medial meniscus. F, femur; T, tibia. Source: reproduced from reference[9] with permission of SAGE Publications.

Tear orientation and fibre disruption

There are three categories of tear, with respect to the plane of the meniscus: vertical, horizontal and complex. These are illustrated in Figure 5.

Vertical tears, which are the most frequent, are subdivided into: vertical longitudinal (including flap, bucket handle and menisco-capsular 'ramp' lesions), which disrupt the superficial radial fibres; vertical radial tears (including meniscal root tears) that disrupt the circumferential fibres; and vertical oblique tears (including 'parrot beak' tears) that disrupt a mixture of both the radial and circumferential fibres.

Vertical longitudinal tears (Figure 5a) are most common, and their biomechanical effects depend on the distance from the periphery. Resection can result in tripling of contact pressures. These tears are typically located in the peripheral third (the vascular zone) of the posterior segment, and have high healing potential. Untreated tears up to 10 mm in size observed at ACL reconstruction had re-operation rates of 3% versus 12% for untreated tears more than 10 mm, suggesting that small vertical longitudinal tears may heal (or at least become asymptomatic) without repair.[11]

Bucket handle tears (Figure 5b) are full-thickness vertical longitudinal tears extending sufficiently anteriorly such that the inner segment may become mobile and displace into the intercondylar notch, causing a mechanical block to extension, or

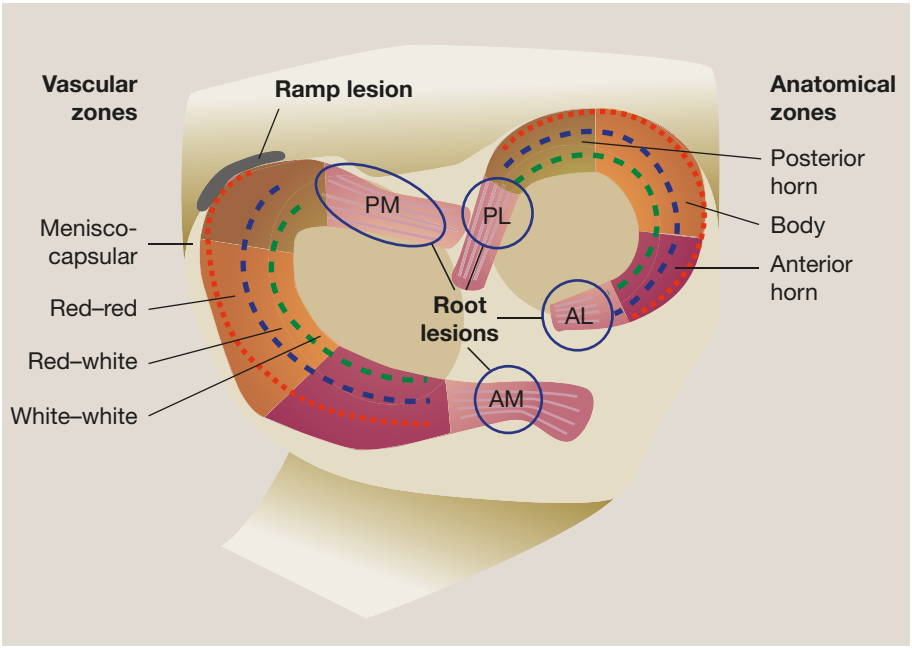

Figure 4 Anatomical classifications of meniscal tear location.[34] Vascular zones: menisco-capsular (peripheral), Red:Red (0–3 mm from the periphery), Red:White (3–5 mm from the periphery), White: White (5–7 mm from the periphery). Anatomical zones: posterior horn, body and anterior horn. Meniscal root tear locations: PM, posteromedial; PL, posterolateral, AM, anteromedial, AL, anterolateral.

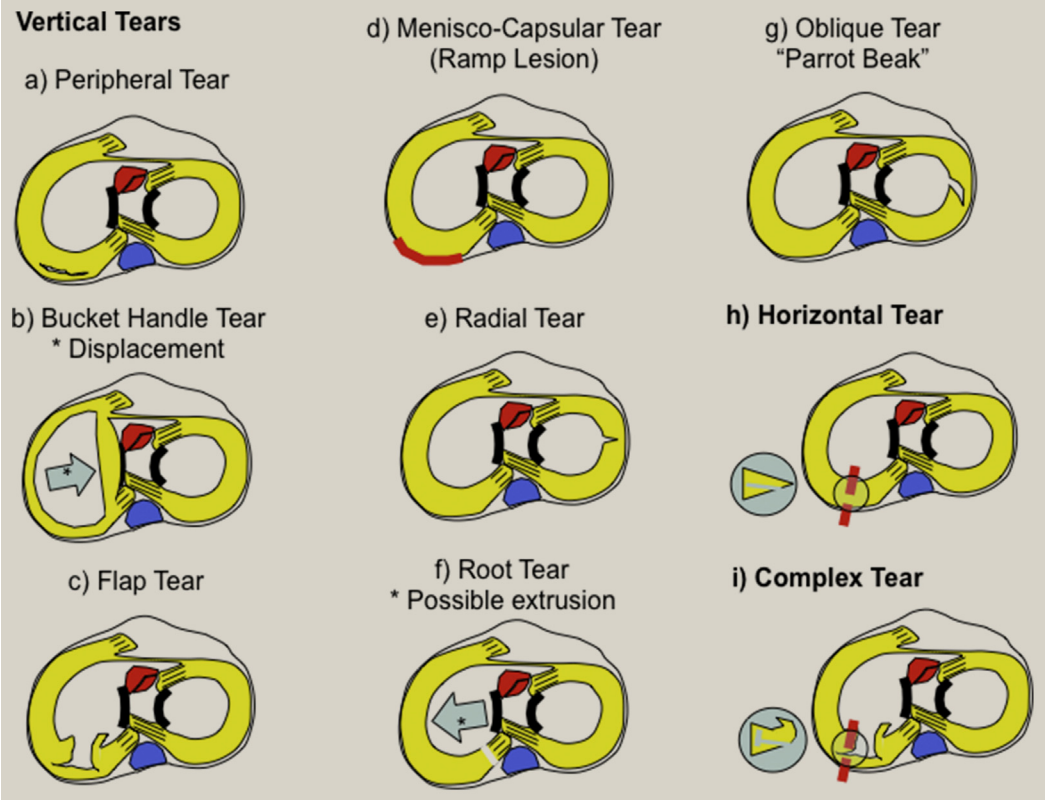

Figure 5 Descriptive classification of meniscal tears based on tear orientation and meniscal fibre disruption shown on a superior view of a right knee. Anterior cruciate ligament insertion shown in red. Posterior crucuate ligament insertion shown in blue. MM = medial meniscus (left), LM = lateral meniscus (right). Tear types: (**a**) vertical longitudinal peripheral tear (posterior horn of MM); (**b**) vertical longitudinal displaced 'bucket handle' tear (of MM); (**c**) vertical longitudinal flap tear (posterior horn of MM); (**d**) vertical longitudinal menisco-capsular tear (of MM); (**e**) vertical radial tear (body of LM); (**f**) meniscal root tear (posterior root of MM); (**g**) vertical oblique 'parrot beak' tear (body of LM); (**h**) horizontal tear (posterior horn MM), with the horizontal component shown on the inset sagittal image; (i) complex tear (posterior horn of MM) with the vertical flap component shown on the superior view and the horizontal and flap components shown on the inset sagittal view.

'locking'. If not treated expeditiously the displaced fragment can cause damage to the articular surfaces.

Flap tears (Figure 5c) may be full or partial thickness and may displace superiorly or inferiorly into the parameniscal gutter and become trapped underneath the meniscus, between the deep medial collateral ligament (MCL) and the tibial plateau, causing tenting and irritation of the MCL and/or the adjacent tibial plateau. Posterior horn flap tears may become wedged behind the posterior condyles or in the notch, and a bucket handle tear may progress to a flap tear if the bucket handle ruptures, resulting in one or two free ends.

Menisco-capsular 'ramp' lesions (Figure 5d) are peripheral vertical longitudinal tears at the menisco-capsular junction of the posterior horn of the medial meniscus, and are associated with increased mobility of the posterior horn. The tend to occur in association with ACL injuries, and they may not be identifiable on MRI or even at arthroscopy without specifically probing the ramp area from a posteromedial portal and viewing through the notch area. For this reason, they have been described as 'hidden lesions', and a classification for ramp lesions has been proposed by Sonnery-Cottet.[12,13]

Vertical radial tears (including root tears) represent a break in the continuity of the longitudinal collagen fibres within the meniscus, and when complete they effectively de-function the entire meniscus. They are most common in the middle segment laterally or the posterior third medially. Lesions of up to 60% of the inner zone (Figure 5e) have no effect on pressure magnitude and are generally trimmed or 'saucerized' to stable tissue. Lesions reaching the peripheral zone, involving over 90% of the meniscus, disrupt resistance of hoop stresses with functional consequences similar to total meniscectomy, and should be repaired, as repair can return peak pressures to normal.

Meniscal root tears (Figure 5f) are radial tears that occur at the strong ligamentous root attachments of the anterior or posterior horns, de-functioning the meniscus. The importance of such tears has only recently been appreciated, as techniques to repair and reattach the roots have become available. The anterior roots, which have relatively simple planar insertions, are rarely injured but are at risk of iatrogenic injury during ACL tibial tunnel drilling. Both medial and lateral posterior root tears (PRTs) are associated with ligamentous injuries, and the presence of concomitant ligamentous injuries should increase the index of suspicion for root lesions. Medial meniscal extrusion of more than 3 mm on a mid-coronal MRI image may be a sign of medial meniscal PRT. The lateral meniscus may not show any signs of extrusion due to anchoring via the menisco-femoral ligaments. A 'ghost' sign, due to absence of meniscal tissue in the region of the site of meniscal attachment on a sagittal MRI image is a characteristic finding, but scans need careful scrutiny to identify the lack of meniscus on one single slice.

The lateral meniscal posterior root is reported to be an important restraint to pivot shift, with tears contributing to high-grade pivot shift in 7–9% of ACL injuries. Biomechanical studies of medial root tears report an increase in contact pressures comparable to total meniscectomy, and recent studies have suggested that a medial root tear may be associated with rapid onset OA or spontaneous osteonecrosis of the knee (SONK). A systematic review reported that 50–100% of SONK patients have root tears.[14]

Vertical oblique tears (Figure 5g) (including parrot beak tears) disrupt a mix of radial and longitudinal elements, and by definition cross into the avascular zone. Management depends (as with radial tears) on the degree of extension into the peripheral zone.

Horizontal tears (Figure 5h) occur in the plane of the meniscus parallel to the articular surface. They cause delamination but minimal fibre disruption, as both radial and circumferential fibres remain largely intact. Occurring most commonly in the posterior third of the meniscus, they can be associated with a discoid meniscus, with degenerative change and with parameniscal cyst development. As the circumferential fibres remain intact, no difference in contact surface area or contact pressure has been detected as a consequence of these tears. Resection of a single leaf, however, reduces contact areas by 59%, possibly by reducing the meniscal 'wedge effect', and produces peak pressures similar to dual leaflet resection. These tears were once thought to have minimal healing capacity, particularly as horizontal tear patterns occur commonly in older patients where they are associated with degenerative changes and OA. However, in young patients, healing similar to other tear patterns has been observed, with a healing rate of 78% reported in a systematic review of nine studies.[15]

It is important to distinguish traumatic horizontal or vertical tears from degenerative tears in patients over 50 with OA. Complex tears (Figure 5i), which include a mixture of horizontal and vertical components, are most commonly degenerate in aetiology, resulting from repetitive physiologic forces leading to gradual attrition of the menisci, and are often accompanied by osteoarthritis. Traumatic tears, occurring as a result of supra-physiologic forces applied to the knee, are more likely to be radial or vertical longitudinal, and often occur in association with ligamentous disruption.

Meniscal tears associated with ACL injuries

The incidence of meniscal injuries in combination with ACL injuries is high, and management is important. Lateral meniscal tears occur in around 20% of ACL injuries, and their incidence does not increase over time, suggesting that most occur at the initial time of ACL injury. Medial injuries however, become more frequent over time, and are more common. The largest study to examine the relationship between meniscal and ACL injuries is based on the results of the Norwegian National Registry. It shows an increased risk of articular cartilage injury of 1.006 per month and medial meniscus injury of 1.004 per month post ACL-injury.[16]

The combination of ACL and meniscal rupture results in higher grades of instability. ACL rupture alone has been shown in cutting studies to increase AP laxity up to 6 mm at 20° flexion. Additional meniscus rupture doubles AP laxity to 12–13 mm. ACL reconstruction alone reduces laxity to 9 mm, with ACL reconstruction plus meniscal repair further reducing laxity to 3–4 mm, almost to the intact state of 2 mm laxity at baseline. From this work, meniscus preservation or repair is particularly important in ACL-injured knees, reducing residual laxity.[17,18]

Meniscal repair

Indications for repair

Meniscal repair has been shown to be superior to resection in terms of function, return to sport and cartilage protection. In

addition, when a repair fails, the amount of secondary resection will usually not be higher than if resection was performed primarily, suggesting a repair should always be attempted where possible. However, there may be secondary damage following failure of a meniscal repair, and factors associated with successful healing should be taken into account during the surgical decision-making process.

Repair techniques

Sutures or devices to repair the meniscus can be delivered via inside-out, outside-in or all-inside techniques. The tear location and orientation determine the optimal technique for suture placement. As a rough guide, repairable tears include those less then 4 mm from the meniscal rim, ideally within 4 weeks of injury and in patients who will comply with the necessary rehabilitation, avoiding sport for 4 months minimum (a personal 'rule of 4s' from the authors). There are, however, no definitive criteria for repairability.

Inside-out remains the gold-standard meniscal repair technique, with sutures passed using a curved cannula through the meniscus and subsequently tied over the capsule (Figure 6). Inside-out techniques are particularly useful for longer tears (>3 cm) or bucket handle tears. With this technique, the middle third and most of the anterior third can be reached. All-inside fixation devices such as Fas-TFix (Smith & Nephew) are particularly useful for posterior third tears, reducing the risk of neurovascular injury from outside-in needles. They can also be used in middle third tears. All-inside and inside-out techniques have been shown to have equal healing rates, functional outcomes and complications.[19] Outside-in techniques can be useful for anterior third tears that are difficult to reach.

Vertical longitudinal tear repair

Acute peripheral vertical longitudinal tears demonstrate good capacity for healing (72%–94% reported).[19] Biomechanically, a stacked vertical mattress suture configuration using in-to-out sutures or all-inside techniques every 3–5 mm has been shown to provide superiority over horizontal mattress.[20] Repaired tears in the red-red or red-white zones lead to good and excellent clinical mid-term results. However, even without repair, tears in this region can do well. In a systematic review of tears diagnosed but left *in situ* without repair at the time of ACL reconstruction, secondary meniscectomy rates were 0–1.5% for lateral small (<1 cm) tears, 0%–7% for larger lateral meniscus tears and up to 15% for medial meniscus tears.[21] As the risk of secondary meniscectomy is higher for medial than lateral meniscal tears, indications for surgical repair are more strict for medial tears.

Menisco-capsular 'ramp' lesion repair

The natural history of the ramp lesion is not well-established, but the risk of tear extension and low morbidity of meniscus repair have been suggested as arguments for repair, which can be performed using an all-inside technique via a posteromedial portal[13] or via fixation from anterior using all-inside devices.

Radial tear repair

Radial tears within the inner 60% of the meniscus with an intact periphery do not compromise overall function, and can be resected. Radial tears extending to the peripheral zone cause complete loss of meniscal function, and should be repaired, if possible, to restore integrity of the rim. Inside-out and anchor-based all-inside techniques with horizontal mattress-suture configurations at the tear site generate tension against the periphery of the meniscus or capsule.

Root repair

True traumatic root avulsions should generally be considered candidates for repair, where possible. On the lateral side a large ligament of Humphry may still provide sufficient restraint to extrusion, such that formal root repair may not be necessary. The meniscal root consists of 3 parts: ligamentous mid-substance, root ligament and the transition zone between the ligament and the body. The transitional zone is the weakest link and the most common site of most root tears. A complete tear in this area (less than 9 mm from the root) corresponds to a Type 2 tear according to the classification proposed by LaPrade et al.[22] and represents 68% of injuries.

Lesions can be repaired by trans-osseous tibial re-insertion or all-inside techniques. A high anterolateral portal position, MCL pie-crusting and removal of PCL synovium aid viewing posteromedially. The meniscal stump is mobilized and the tibial insertion site is prepared. Tip aimers are used to insert a 2.7 mm passing pin, which is overdrilled with a 4.5 mm cannulated drill bit. A suture delivery device such as the 'Knee Scorpion'

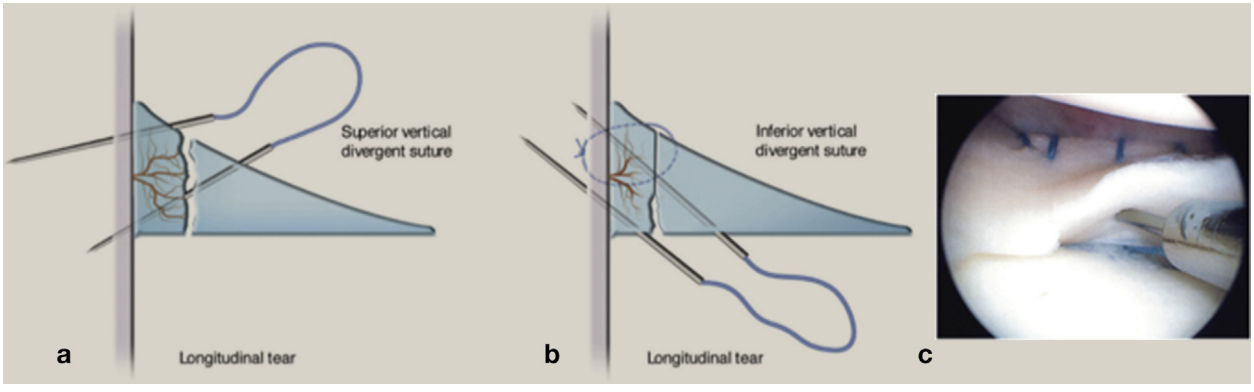

Figure 6 Double-stacked inside-out vertical suture technique performed in the repair of a vertical longitudinal meniscal tear. (**a**) The superior sutures are placed first to close the superior gap and to reduce the meniscus to its bed. (**b**) Then, the inferior suture is placed through the tear to close the inferior gap. (**c**) Arthroscopic photograph of a vertical longitudinal meniscal repair performed using an inside-out suture technique. Source: reproduced from reference[35] with permission of SAGE Publications.

(Arthrex, DE) is used to pass either a tape suture or high strength suture through the meniscal stump. Sutures are retrieved via the tibial tunnel and are tied over a button device.

Horizontal tear repair

A horizontal cleavage tear in young athletes is a rare specific condition not to be confused with horizontal tears associated with degeneration and early OA. In younger patients, horizontal tears can be regarded as an overuse micro-traumatic lesion in stable knees, even if histological samples demonstrate some mucoid degenerative tissue. When functional treatment fails, meniscus repair can be considered. Pujol et al. proposed an open approach.[23] Meniscus repair is performed with vertical sutures. Injection of PRP or insertion of fibrin clot could enhance the healing process, and preliminary results are encouraging, demonstrating better results in terms of functional scores and secondary meniscectomy.[24] Again, this treatment has to be compared with a meniscectomy, which is subtotal and which would provoke early advanced osteoarthritis, especially on the lateral side.

Repair enhancements

Several methods have been proposed to enhance healing of the meniscus. The results have been summarized in a recent review by Woodmass et al.[25]

Marrow venting procedures aim to replicate the biological environment created by ACL tunnel drilling, and have been shown to be effective in a goat model, but at 2-year follow-up no clinical benefit in humans has been observed. Similarly, mechanical stimulation (synovial rasping and abrasion of tear surfaces) promotes neovascularization in a rabbit model, but has failed to show a clear benefit in humans.

Trephination, to create channels from the vascular to avascular areas, has demonstrated improved healing in a goat model and 90% good to excellent results in humans, but without a comparison group. Fibrin clot has also shown high success rates, but it is a difficult technique to perform. Bone marrow aspirate injection in combination with all-inside repairs in the avascular zone have shown 86% clinical improvement and 76% non-homogeneous MRI with no evidence of a tear, but again without a comparison group. Platelet-rich plasma (PRP) has been investigated by two human trails, which have not shown any difference in outcomes. One study has reported good results with PRP injection after repair for the specific indication of horizontal cleavage tears in athletes, but again without a comparison group.[24]

Stem cell-based therapies in porcine studies have suggested improvements in meniscal repair, but human studies have yet to be performed. There is encouraging evidence of increase in meniscal volume following stem cell injections and promising early results from the use of a fascial sheaths to cover meniscal repairs.

Overall, whilst there is encouraging evidence from animal models and case series in humans that repair enhancement techniques may improve healing rates, most techniques have yet to be evaluated in well-designed clinical trials.

Rehabilitation

Tear patterns determine postoperative rehabilitation. For example, vertical tears are compressed during weight-bearing whilst radial tears are distracted. Currently, there is no evidence for improved results with accelerated rehabilitation, and to prevent misinterpretation the authors of this review employ a single standardized protocol for all repairs. As meniscal loading is increased in flexion, immediate weight bearing is allowed only in a splint locked in extension with non-weight-bearing flexion allowed to 90°. From 4 weeks the splint is removed, and full weight-bearing allowed from 0° to 90°. Squatting beyond 90°, pivoting, twisting and cutting are avoided until 3 months. Return to sport is typically at 4–6 months.

Repair failure and revision repair

Meniscectomy rates after repair of 0–44% are reported, with a mean of 15%.[26] In carefully selected patients, revision repair can be effective, and success rates of 79% are reported at 5 years.[27] Irreparable tears should undergo partial meniscectomy, preserving as much meniscus as possible.[28]

Meniscal allograft transplantation

Although repair in young individuals is strongly advocated, it is not always possible to preserve a torn meniscus. In addition, as mentioned above, approximately 15% of repaired menisci will fail and will require secondary meniscectomy. Post-meniscectomy patients who go on to develop activity-related pain in the involved compartment may warrant consideration for meniscal allograft transplantation (MAT). Currently, there is little evidence that prophylactic meniscal reconstruction is beneficial. Animal studies and one recent pilot RCT on MAT have indicated a strong potential for a chondroprotective effect, but there are no long-term studies, and in general meniscal transplantation is reserved for patients with significant symptoms.[29]

When assessing suitability for meniscal transplantation it is important to take into consideration the key factors of limb alignment, ligamentous stability and articular surface damage that will need to be dealt with via additional surgery that can be either staged or simultaneous. A history of symptoms, previous injuries and previous surgery should be taken, along with weight-bearing flexed knee radiographs and long-leg alignment views. MRI is used to assess ligamentous integrity, articular surfaces (with measurement of any areas of cartilage loss or subchondral oedema) and also for graft sizing measurements. In cases with previous ligament reconstruction, CT scanning may be indicated to assess tunnel size and position.

The ideal candidate for MAT is a patient who is young to middle aged (probably up age 55) with no evidence of advanced OA (less than ICRS grade 3b). However, although full-thickness chondral loss (Outerbridge IV or ICRS 3b or 3c) was traditionally considered a contraindication, surgeons have stretched the indications to selectively include such patients, accepting a slightly higher failure rate in these patients and combining MAT with osteotomy, stabilization and articular cartilage grafting or osteochondral allografting when indicated.

Surgical technique

Meniscal transplantation is performed using a combination of meniscal root and peripheral repair techniques. During the early days, pioneer surgeons used an open approach, with detachment of the affected compartment's collateral ligament or use of a joint

distractor. Current isolated MAT involves implanting an appropriately size and side-matched donor meniscus by a variety of arthroscopically-assisted techniques.

Sizing is a critical step and is based on X-ray or MRI measurements. Fresh-frozen donor menisci are obtained via tissue banks e.g. UK NHSBT Tissue Services (Liverpool, UK). Strict adherence to donor screening by the tissue banks is vital to ensure that the risk of disease or infection transmission is minimized. Once an appropriately sized graft has been identified, it can be shipped to the required hospital.

The graft is prepared according to the desired technique for fixation of the meniscal roots to the tibia. This can be with a bone-bridge (an intact bone block extending between the two roots), individual bone blocks or sutures at each end of the graft.

The bone bridge technique is performed arthroscopically-assisted, and the graft is introduced via a mini-arthrotomy into a corresponding groove prepared in the tibia. This technique has the advantages of maintaining the integrity of the meniscus to its bony attachments, to maintain its function in resisting hoop stresses, and it gives bone-to-bone healing of the graft. However, graft sizing must be exact, with no intra-operative 'fine-tuning' possible.

With bone blocks at each end and with the suture fixation technique, the meniscal allograft is secured via bone tunnels positioned at the meniscal roots. The graft can be parachuted into the knee using traction sutures via an extended arthroscopy portal. With bone plugs, there is still bone-to-bone healing, and the surgeon can perform a little fine-tuning of the meniscal sizing through minor adjustment of the tunnel positions. With a free meniscus graft (with no bone block or plugs) the surgeon has the greatest control over adjustments in sizing, with the option to pull the meniscus slightly into the tunnel aperture at each end before tying the sutures over a bone bridge on the tibia. With all three techniques, the peripheral margin of the meniscus is sutured to the capsule using a mixture of in-to-out and all-inside suturing techniques, similar to when repairing a large bucket handle (Figures 6 and 7).

The perceived advantages of bone-to-bone fixation are a slight improvement in contact mechanics in biomechanical studies and less meniscal extrusion. However, no differences in patient-reported outcome measures (PROMs) or pull-out strength have been shown. Potential advantages of an all-suture technique without bone plugs are that it is a more minimally invasive and less complicated technique. It may also have histological advantages, as significantly higher cellular viability and collagen organization was found on biopsy of grafts secured by an all-suture technique compared to bone plug fixation. To-date, there is no evidence as to which technique is superior, with no clinical differences demonstrated between them.

The authors favour an arthroscopic all-suture technique via bone tunnels, and details of the technique were published in 2015.[30] This involves dissecting the meniscus off the donor tibial plateau and preparing each end with non-absorbable sutures. The sutures are then led through bone tunnels in the prepared meniscal root insertion sites. The graft is passed into the knee through a working portal and fixed in place with multiple stacked vertical mattress sutures using a combination of all-inside devices and inside-out sutures tied over the capsule. The sutures for the anterior and posterior roots are tied over a bone bridge on the proximal tibia. Figure 7 shows a left lateral compartment intra-operatively before and after allograft insertion.

Postoperative rehabilitation will also depend on any associated procedures performed. Isolated MAT patients mobilize non-weight-bearing for 4 weeks before commencing partial weight-bearing using an unloader brace for a further 2 weeks. After 6 weeks they are allowed and encouraged to commence weight-bearing in an unloader brace for a further 6 weeks, with flexion limited to 90° until 3 months. An example of a rehabilitation rehabilitation protocol is given on the website www.meniscaltransplant.com.

Biomechanical outcomes

A number of biomechanical studies have compared the load-sharing ability of meniscal allografts with the native meniscus, as well as a knee with no meniscus. Paletta et al. used young human cadaveric knees to test the total contact area and peak contact pressure changes following meniscectomy, and then after

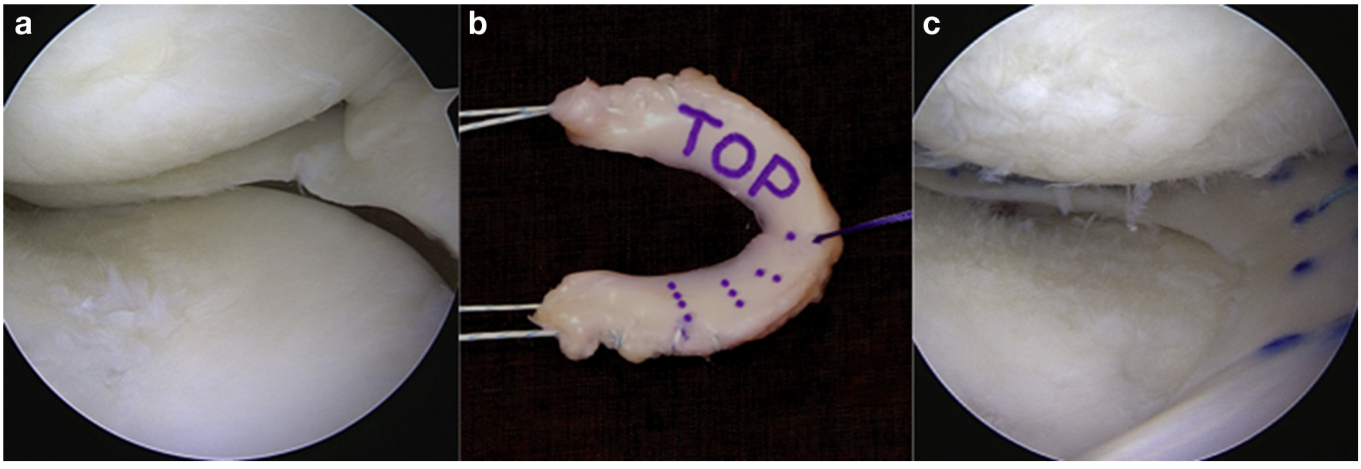

Figure 7 Meniscal allograft transplantation (MAT): (**a**) Arthroscopic image of lateral meniscal deficiency showing less than 3 mm residual meniscal rim and meniscal extrusion. (**b**) Lateral MAT graft prepared using an all suture technique with lead sutures at each root and a further traction suture just anterior to the popliteal hiatus. (**c**) Arthroscopic image of the knee shown in (**a**) with the MAT graft sutured into position. Images courtesy of Mr T. Spalding.

subsequent allograft transplantation. They found that the total contact area decreased by 45–50% following meniscectomy and then increased by 42–65% after allograft transplantation (compared with meniscectomy scores) at all knee flexion angles.[8] They also found that peak contact pressures increased by 235–335% following meniscectomy, and were decreased by 55–65% after allograft transplantation at all knee flexion angles. The improvements following transplantation did not, however, reach the level of the native knee. More recently, McDermott el al. reported a human cadaveric study comparing the native knee with an all-suture allograft fixation, a bone plug fixation and meniscectomy.[31] They found that both the bone plug technique and the all-suture technique of allograft fixation significantly reduced peak contact pressures compared to meniscectomy. They also found that the peak contact pressures of the knees with meniscal allografts (either technique) were not significantly different to the native knee. These results support the hypothesis that a meniscal allograft functions in a similar way to a native meniscus. However, there are limitations to the application of these cadaveric results to patients, and in living patients the meniscus is subject to a different immunological, biochemical and biomechanical environment.

Clinical outcomes of MAT

The overall goal of MAT is to achieve symptom-free activities of daily living without swelling or pain, and hopefully prevent progressive chondral damage and OA. Systematic reviews of the outcomes following MAT show clinically meaningful improvements in all patient reported outcome measures at final follow-up. A recent systematic review reported Lysholm scores increased from 55 to 81, with an overall complication rate of 10%.[32] Complications include removal of prominent fixation sutures, resection of scar tissue, investigation of ongoing pain, and tearing of the edge of the meniscus. There are few long-term survival studies, but 80% survival at 10 years, 50% at 15 years and 20–40% at 20 years have been reported. Early to mid-term evidence, based on plain radiographs and MRI, suggests MAT may offer some chondroprotective benefit.[33]

For young and active patients it has to be considered that a meniscal transplant will almost inevitably 'fail' within the patient's lifetime. However, MAT is likely to give at least 10–15 years of optimized function and comfort whilst delaying a first arthroplasty. This time gained may be regarded as success, provided certain pre-defined expectations are met, and could potentially save the patient from revision arthroplasty within their lifetime.

Discussion

The goal of meniscal surgery continues to be restoration of knee function, but the horizon has shifted from the initial functional improvement to long-term outcomes. The importance of the menisci in protecting the knee joint is now well recognized, and the modern aims of treating meniscal lesions are thus both to restore knee function and to delay degenerative change. This requires repair and preservation of the meniscus.

Surgical decision-making should take into consideration patient factors such as age, general health and activity levels; tear characteristics such as type, size and location; and general condition of the knee i.e. associated chondral damage, ligament laxity and alignment. Bucket handle and root tears should be treated expediently to avoid articular cartilage damage. A high index of suspicion and familiarity with injury patterns aids early and accurate diagnosis of meniscal lesions. Surgery for degenerative tears is controversial, and there is now a consensus that in most cases they should initially be treated conservatively. Use of biologics, for example PRP or mesenchymal stem cells, may increase healing rates but robust evidence is currently lacking.

If repair is not possible and if the patient develops post-meniscectomy symptoms of pain on activity, meniscal reconstruction by allograft transplantation has been shown to relieve pain and improve quality of life in a young patient population. There has been an evolution in techniques from open surgery to arthroscopically-assisted methods, and graft complications are now low following advances in tissue bank provision and infection control. Patient-reported outcomes show maintenance of clinical benefit in the long-term, and indications for transplantation are being extended as results improve.

Understanding the significance of different patterns of meniscal deficiency and combined pathology, such as ligamentous instability or malalignment, helps the surgeon to identify knees at risk of rapid failure and address reconstruction priorities: alignment, stability, menisci and finally, articular surfaces, as necessary.

While the evidence is not yet conclusive for a chondroprotective effect, there is growing evidence that both isolated MAT and combined surgery with ligament reconstruction, osteotomy and cartilage repair can give significant functional and symptomatic improvements for patients with post-meniscectomy symptoms. ◆

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