Review article

GRAFT SELECTION IN RECONSTRUCTION OF THE ANTERIOR CRUCIATE LIGAMENT

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Only 20 years ago reconstruction of the anterior cruciate ligament (ACL) involved an open intra-articular operation in which the graft was placed in a position where it was not anatomical and which involved opening both the medial and lateral capsules. There was a long scar and considerable analgesia was required after the operation. The patient remained in hospital for ten days and in a cast for six weeks. Now, a less invasive procedure allows positioning of the graft to give a full range of movement without impingement and with restoration of stability.

Which type of graft is now used? A poll of members of the Australian Knee Society in 2000 revealed that all used autograft only, with 58% employing both patellar tendon and hamstring grafts in certain circumstances; the remainder were evenly divided in their preference for 'only' patellar tendon or 'only' hamstring.¹ Members of the ACL Study Group showed a different perspective, with 73% choosing the patellar tendon, 23% the hamstrings and 4% 'others', such as allografts. This had not changed from a previous survey two years earlier.² Another survey of orthopaedic surgeons caring for American football teams in the major leagues showed that all but one chose autologous patellar tendon grafts.³

This article evaluates the available choices of graft and examines their advantages and disadvantages, the clinical outcomes, morbidity at the donor site, biomechanical characteristics and healing. We consider whether certain grafts are more suitable in particular cases and speculate as to the future directions of surgery of the ACL considering tissue engineering, growth factors and gene therapy.

Choices of graft

Autografts

Biomechanical comparison. Wilson et al⁴ studied the biomechanical properties of 15 matched pairs of central-third bone-patellar tendon-bone and double-looped semitendinosus/gracilis grafts harvested from 15 cadavers with a mean age of 40 years. The mean load to failure for the patellar tendon grafts was 1784 ± 580 N, compared with 2422 ± 538 N for the hamstring tendons. There was no significant difference in stiffness between the two. The elastic modulus was 225 MPa for the patellar tendon and 145 MPa for the hamstring tendon grafts. The mean cross-sectional area of the hamstring grafts was 57 mm^2 compared with 45 mm^2 for those from the patellar tendon.

Simonian et al⁵ cyclically tested grafts 10 mm wide from the central-third patellar tendon and from doubled semitendinosus and gracilis tendons obtained from six fresh frozen cadavers for 1000 cycles from 0 to 300 N. They found no significant differences in the strain, stress or modulus between the two.

Harris et al⁶ examined the strength of the central quadriceps tendon as compared with the central-third of the patellar tendon in 15 preserved and six fresh frozen specimens. The quadriceps tendon was found to be 1.8 times thicker and 1.36 times stronger than a patellar tendon graft of comparable width. Staubli et al⁷ analysed the mechanical properties of 10 mm wide, full-thickness central parts of the quadriceps and patellar tendons from paired knees of eight male donors with a mean age of 24.9 years. The specimens were tested unconditioned and after cyclic preconditioning. The mean cross-sectional area of the quadriceps tendons was significantly larger than that of the patellar tendons ($64.6 \pm 8.4 \text{ mm}^2$ and $36.8 \pm 5.7 \text{ mm}^2$, respectively). However, the mean ultimate values for tensile stress of the patellar tendons were significantly larger than those for the quadriceps tendons ($53.4 \pm 7.2 \text{ N/mm}^2$ and $33.6 \pm 8.1 \text{ N/mm}^2$, respectively).

There is a wide variation in the values reported in the literature but those commonly quoted are listed in Table I.

Morbidity of the donor site

Pain. A long-term follow-up of ACL reconstructions for a minimum of seven years⁸ showed that patients scored a mean of 79 points on a pain scale, with 100 equalling no

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Table I. Accepted values for ultimate tensile load and stiffness

	Ultimate tensile load (N)	Stiffness (N/mm)
Native ACL ¹³⁹	2160	242
Doubled semitendinosus/gracilis ¹⁴⁰	4140	807
Bone-patellar tendon-bone (10 mm) ¹⁴¹	2977	455
Quadriceps (10 mm) ⁷	2352	326
Bone-patellar tendon-bone allograft fresh frozen ¹⁰²	2552	633
Bone-patellar tendon-bone allograft after 3 Mrad irradiation ¹⁰²	1990	531

pain. The grade of patient satisfaction correlated more highly with the absence of pain than with any other variable assessed.

When questioned closely, patients will often admit to pain. In comparative series anterior knee pain was experienced in seven of 38 patients with a semitendinosus/gracilis graft compared with 23 of 35 with a patellar tendon graft, one year after operation.⁹ In those with a hamstring graft the pain was mild in five and moderate in two whereas with the patellar tendon procedure 19 had mild and four moderate pain. Anterior knee pain is commonly attributed to the use of the patellar tendon. The reported incidence of retro-patellar pain is variable, ranging from 4% to 40%.¹⁰⁻¹⁴

D'Agata et al¹⁵ studied the area of patellofemoral contact and pressure after harvesting of the central-third of the patellar tendon in five cadaver knees. By using pressure-sensitive film and isometric quadriceps forces, the contact area and pressure were measured in each specimen in the normal knee, after removal of the graft and after closure of the tendon defect. Neither harvesting the central 10 mm of the patellar tendon nor closing the gap significantly altered the area of patellofemoral contact or the pressure. However, Friis et al¹⁶ using thermoelastic analysis showed that stresses on the anterior surface of the patella were significantly greater when the bone block had been excised than in the intact patella. Following hamstring grafting patients may experience symptoms at the donor site⁹ which may be of concern in football and in sprinting sports.

The size of the operation scar has usually been considered to be of cosmetic relevance only. However, patients are concerned by loss of sensation and Kartus et al¹² showed that this correlated with difficulty in kneeling and walking.

Power. There is a demonstrable loss of power in the associated muscles after repair of the ACL. A follow-up at seven years of patients who had received a patellar tendon graft showed persisting loss of both concentric and eccentric quadriceps power. This group of 30 patients also had some hamstring weakness.⁸ The measurements were obtained using an isokinetic dynamometer at 60° per second, which is a comfortable speed for testing eccentric strength. Concentric quadriceps power was 85.8% of normal, eccentric quadriceps power 92.8% and concentric hamstring power 94.9%. Only concentric quadriceps power showed some correlation with the grade of patient satisfaction.

The effect of using the central-third of the patellar tendon on the strength of the quadriceps muscle has been a cause for debate. Studies which evaluated knees after operation consistently showed significant deficits in quadriceps strength.^{14,17,18} The smallest loss occurred in patients¹⁹ who had an aggressive postoperative programme of rehabilitation. The quadriceps deficit was attributed to harvest of the graft.¹⁴

In order to determine whether the quadriceps deficit is due to the knee injury itself or to harvest of the graft, the strength of the quadriceps has been compared after reconstruction of the patellar tendon by allograft and autograft. Other studies^{20,21} have shown relative quadriceps weakness with no difference between allograft and autograft. No difference in quadriceps strength was noted when hamstring grafts were compared with those of the patellar tendon.²² Further insight is gained when knees which have been treated conservatively after rupture of the ACL are evaluated. Wojtys and Huston²³ compared 40 normal knees with 100 with cruciate deficiency; 21.4% of males and 33.5% of females had a quadriceps deficit. Lorentzon et al²⁴ examined 18 patients with chronic damage to the ACL and found a deficit of 13% to 29% in the injured limb.

Ten patients were studied in whom the patellar tendon graft was taken from the normal knee for reconstruction of the opposite unstable joint.²⁵ Before operation the unstable knee had the weaker quadriceps. Both knees took 15 months to recover but the unstable knee remained the weaker, despite harvest of the graft from the normal knee. It is interesting to speculate on this persisting weakness. Clearly, normal function was not restored. This may be due to damage to the articular cartilage or meniscus or, as suggested by Corrigan, Cashman and Brady,²⁶ there may be some proprioceptive benefit from hamstring dominance in the ACL-deficient knee.

A prospective comparison was made between 38 patients undergoing reconstruction of the ACL with a semitendinosus/gracilis graft and 35 with a graft of one-third of the patellar tendon. At one year both hamstring and patellar tendon grafts showed an approximate loss of 10% of quadriceps power compared with the normal opposite knee. The semitendinosus/gracilis graft showed a loss of 10% of hamstring power whereas the patellar tendon group showed a slight increase. Hamstring power may improve with time. In a series of 31 patients in an older age group assessed at a

mean of four years after operation, ten had a patellar tendon graft and in 21 the hamstrings were used.²⁷ There was no difference between the groups with each having 102% of hamstring power compared with the contralateral leg. Both had 95% of power of extension.

Other studies have compared muscle strength with a patellar tendon or hamstring graft. Carter and Edinger²⁸ evaluated 106 patients at six months and showed no statistically significant difference in the strength of isokinetic flexion and extension. Similarly, Aglietti et al²⁹ prospectively studied 60 patients at a mean of 28 months and found no significant difference in peak torque in extension or flexion. Hiemstra et al³⁰ found that after one year, deficits in the strength of knee flexion of up to 50% were observed only in the hamstring tendon group with the greatest loss occurring beyond 60°. Similarly, deficits in the strength of extension of up to 50% between 60° and 95° were observed only in the patellar tendon group.

Length of the patellar tendon. Shaffer and Tibone³¹ in a prospective study of patients with arthroscopic reconstruction of the ACL using the middle third of the patellar tendon with the defect closed, found a mean of 2.28% of shortening of the tendon. Muellner et al¹³ found no correlation of anterior knee pain with shortening of the patellar tendon.

Other studies have described shortening of the patellar tendon after harvest of the graft.^{10,13,32}

Fracture of the patella. Christen and Jacob³³ reported six longitudinal fractures of the patella at the time of harvest. We have also noted this extremely rare complication due to errors in surgical technique when using osteotomes or with unnecessarily deep saw cuts. There may be a predisposition to late fracture. However, this appears to be very slight and has not prevented orthopaedic surgeons from choosing the patellar tendon as the most popular graft in contact football.³

Morphology of the donor tendon after harvest. After harvest of the middle third of the patellar tendon, extensive scar formation has been noted with poor orientation of the collagen fibres.^{34,35} In the dog³⁶ the donor tendon after six months showed failure on loading of 60% of the control group; stiffness was reduced to 70% and modulus to 33%. The results of closing or leaving the tendon defect open are comparable in terms of pain, the radiographic appearance and isokinetic testing.³⁷⁻³⁹

Other studies with MRI^{40,41} have shown reconstitution of the semitendinosus and gracilis tendons, often with a more proximal attachment. They did not show hypertrophy of the semimembranosus or biceps femoris muscles.

Healing of the graft to bone. The ligament-bone interface is a highly specialised site designed to diminish stress concentration at the interface of the soft and hard tissue. The insertion may be direct or indirect. Direct insertion shows four distinct zones: ligament, unmineralised fibrocartilage, mineralised fibrocartilage and bone. The femoral origin of the ACL is a direct insertion. Indirect insertions

contain collagen fibres which blend with periosteal collagen fibres, which in turn are anchored to the adjacent bone without a fibrocartilage layer. Indirect insertions contain Sharpey's fibres, which are collagen fibres that are continuous from ligament to bone. An example is the insertion of the medial collateral ligament into the tibia. Direct insertions are typically associated with long tendons inserting into small areas of bone, while indirect insertions are usually short tendons inserting into a large area.

It is widely believed that healing of the graft in the bone tunnel is faster with a patellar tendon bone block construct than with a free tendon.

Patellar tendon. In a study in rabbits Schiavone et al⁴² described incorporation of the bone block as early as 16 weeks, with re-establishment of the normal four-zone insertion by six to nine months. Yoshiya et al⁴³ has demonstrated complete healing of the bone block at 12 weeks in adult dogs.

Hamstring grafts. Healing at the tendon bone tunnel interface has been evaluated in animal studies.^{44,45} Formation of an indirect tendon insertion by adherence of the tendon to the tunnel wall with Sharpey's fibres was observed by six weeks. One animal study of the pull-out strength of tendon healing in the bone tunnel showed that the graft did not fail by avulsion from the tunnel after 12 weeks.⁴⁵ A biopsy⁴⁶ of two patients who underwent revision ACL reconstruction after early rupture of a hamstring graft showed similar findings. By contrast, Weiler, Hoffman and Bail⁴⁷ have shown direct tendon healing in a sheep model using bio-degradable interference screws in the zone of maximal compression of the tendon.

It has not yet been determined if it is better to leave a tendon free from fixation in a tunnel or whether it should be compressed by an interference screw.

Fate of autografts. Pathological changes occur in autografts after implantation. In a clinical study Rougraff et al⁴⁸ biopsied 23 patellar tendon grafts at varying stages after reconstruction. They describe four stages of ligamentisation. The initial stage of repopulation occurs during the first two months with an increasing number of fibroblasts and active nuclear morphology by three weeks. Over the next ten months, the graft goes through a stage of rapid remodeling in which the fibroblast count increases markedly, the active nuclear morphology and neovascularity remain increased, and more areas of degeneration are present as the percentage of mature collagen decreases. The third or 'maturation' stage occurs over the next two years and is characterised by a slow decline in the nuclei and the maturation of the collagen matrix. By three years the grafts are ligamentous by all the histological criteria examined.

The histological changes of the intra-articular portion of a hamstring ACL graft up to one year in sheep have been reported by Goradia et al.⁴⁹ The grafts showed relative central acellularity at four weeks, with repopulation of this region with spindle cells at eight weeks. The orientation of the collagen fibres was random at four weeks, with longitudinal reorientation peripherally. Disorganisation of

the central area was seen at eight weeks. Directional orientation of the collagen was first identified at 12 weeks, but a uniform crimp pattern was evident only in focal areas. Such a configuration was seen in 50% at 24 weeks and 75% at 52 weeks. The authors concluded that the hamstring grafts were transformed into a histological structure similar to that of a normal ACL.

Animal and human studies^{50,51} have shown deficiencies in graft load to failure in the first 12 months after implantation as compared with the contralateral donor tissue and with the normal ACL. In a study⁵¹ in which the graft was compared with the same one third of the patellar tendon in the opposite normal knee, it showed 53% load to failure at three months, 52% at six months, 81% at nine months, and 81% at 12 months.

A case report,⁵⁰ eight months after reconstruction using one-third bone-patellar tendon-bone, described the linear stiffness of the graft as 90% of the normal contralateral ACL, with an ultimate load to failure 87% of normal. These findings are similar to those seen in animal studies.

Oakes⁵² and Shino and Oakes⁵³ noted a predominance of small collagen fibrils (>100 nm) on electron microscopy of ACL autografts and allografts. This was independent of the type of graft, fixation, rehabilitation or surgeon. Other studies on rabbit tendons showed a strong positive correlation between the diameter of the fibrils, the tensile modulus ($r = 0.74$, $p > 0.05$) and the ultimate load ($r = 0.72$, $p > 0.05$).^{54,55} Hydroxypyridinium (HP) cross-link density was low in the first six months after reconstruction, but had increased at one and three years. A significant correlation ($r = 0.75$, $p = 0.01$) was found between the HP density and Young's modulus. The two biological reasons for the poor long-term strength of patellar tendon autografts are probably the lack of large collagen fibrils and the cross-link density. The dominance of fibrils of small diameter (>100 nm) has been observed in long-term biopsy studies on autografts and allografts in man.^{52,53}

Widening of the tunnel. This was first described in allografts sterilised with ethylene oxide.^{56,57} More recently, a high incidence of widening has been reported in hamstring grafts.^{17,58-61} Other studies^{58,59} have shown a greater incidence in hamstring grafts than with patellar tendon grafts, although a CT study⁶² using the latter demonstrated significant expansion of the tunnel.

Widening of the tunnel was attributed to excessive movement of the graft in the tunnel when using suspensory fixation devices.⁶³ A recent study⁶⁴ evaluated tunnel widening in 259 patients who had undergone hamstring ACL reconstruction with four different fixation devices to test this 'bungy cord effect'. The Endobutton/staples construct had significantly less widening than metal interference screws, bioabsorbable interference screws and a bone mulch screw/staples construct. This suggests that there is a significant biological component which could be attributed to a variable cytokine response to surgery⁶⁵ or a reaction to synovial fluid.

Other studies have shown no correlation between tunnel widening and outcome.^{17,58,60,61}

Driving after reconstruction of the ACL. It is important to determine the optimal time for patients to return to driving after an injury or surgery to the ACL.

In a prospective study⁶⁶ of the braking reaction time before and after arthroscopic reconstruction of the ACL in 73 patients, of whom most had an autologous hamstring tendon graft, 25 normal subjects were also studied as a control group. A braking reaction test was undertaken 24 hours before surgery and every two weeks after for up to eight weeks on a computer-link automobile simulator. The braking reaction time was taken as the interval between display of a red signal and the moment at which 200 N of force was applied to the brake pedal by transfer of the right foot from the accelerator. It was shown that the driving reaction time of patients before surgery was comparable with that of the control group. After operation, it took six weeks for the driving reaction time of the right ACL group, but only two weeks for those who had the operation on the left side, to be equivalent to that of the control group.

In another study⁶⁷ in a group of ten male patients, who had had right ACL reconstruction with autologous patellar tendon graft, the brake response time was found to match that of the 12 normal control subjects as early as four to six weeks after operation.

There appeared to be no difference irrespective of whether the graft was taken from the hamstrings or the patella.

Outcomes

Patellar tendon. In the 1930s Palmer⁶⁸ and Campbell⁶⁹ were among the first to use the patellar tendon for reconstruction of the ACL. In 1963 Jones⁷⁰ described the use of the central third of the patellar tendon which was left attached to the tibial tubercle distally, with a full-length wedge of patellar bone transferred through a drill hole in the lateral femoral condyle. A vascularised patellar tendon graft was attempted by Paulos et al,⁷¹ using the medial third of the patellar tendon and its contiguous neurovascular pedicle from the inferior medial geniculate artery.

A number of studies with a minimum follow-up of five years have been published.⁷²⁻⁷⁵ Using the rating of the International Knee Documentation Committee or Tegner or Lysholm scores, a satisfactory outcome was found in 78% to 90% of patients. Giving-way was eradicated in 78% to 98%. The best results were found in a group of 90 patients who had normal menisci at the time of surgery. The patient rating was 90% normal or nearly normal, 98% had a grade-0 pivot shift and in 97% no degenerative changes were seen radiographically.⁷²

Some studies^{73,75} have correlated the timing of surgery and the state of the menisci and articular cartilage with the outcome. They showed better results if the operation was carried out early and if the menisci and articular cartilage were intact.

The advantages of a patellar tendon graft are: 1) rapid

healing of the bone blocks within the intraosseous tunnels; 2) direct rigid fixation of the bone blocks close to the aperture; and 3) good preservation of load to failure and stiffness.

The disadvantages are predominantly related to the donor site and include: 1) anterior knee pain; 2) patellar tendinitis; 3) rupture of the patellar tendon; 4) fracture of the patella; 5) increased joint stiffness; 6) late chondromalacia; and 7) injury to the infrapatellar branch of the saphenous nerve.

Hamstrings tendon. In 1939 Macey⁷⁶ described the use of the semitendinosus tendon, based distally, for intra-articular reconstruction of the ACL. The tendon was routed through osseous tibial and femoral tunnels and sutured to the periosteum. Lindemann⁷⁷, in 1950, described the transfer of the proximally-based gracilis tendon through the posterior capsule into the intercondylar notch. The graft was fixed to the tibia in an osseous bone tunnel anterior to the insertion of the ACL. Augustine⁷⁸ and Lange⁷⁹ used the semitendinosus with Lindemann's technique. Four-strand hamstring grafts have since become more popular consisting of either doubled semitendinosus/gracilis^{80,81} or quadrupled semitendinosus tendons.⁸²

The advantages of hamstring grafts are: 1) high load to failure and stiffness; 2) a greater cross-sectional area of tendon; 3) easier passage of the graft; 4) a small incision; 5) low postoperative morbidity; and 6) less donor site morbidity.

The disadvantages are: 1) slower tendon-to-bone healing in the tunnel; 2) the possibility of injury to the saphenous nerve; 3) weakness of the hamstring muscles after operation; and 4) widening of the tunnel.

Quadriceps tendon. The use of the quadriceps tendon as a graft for the ACL has been advocated by Staubli et al⁷ and Fulkerson and Langeland⁸³ who documented the good biomechanical properties of this tendon. It is two to three times thicker than the patellar tendon and is usually harvested with a bone block from the superior pole of the patella. Chen, Chen and Shih⁸⁴ described the results of arthroscopic reconstruction of the ACL using quadriceps tendon-patellar bone autograft in 12 patients. After a follow-up of 15 to 24 months, ten returned to their level of preinjury sports and ten had a normal or near normal IKDC score. However, after one year the quadriceps strength was only 80% of the normal knee in 11 patients.

The advantages of this graft are: 1) a thick tendon; 2) good biomechanical properties; and 3) decreased anterior knee pain.

The disadvantages are: 1) weakness of the quadriceps after operation; 2) an unsightly scar; and 3) graft harvest is technically more difficult.

Iliotibial tract. The use of the iliotibial tract for reconstruction of the ACL was first described by Hey Grove.⁸⁵ A strip of fascia lata was detached from its insertion and directed through a tunnel in the tibia. In 1963, O'Donoghue⁸⁶ described a technique in which the iliotibial tract was left attached distally and routed through tunnels drilled in the

tibia and femur. He reported the results on 29 patients of whom 26 had returned to some form of sport.

Bak et al⁸⁷ followed up 40 patients for between two and seven years after reconstruction of the ACL with an autograft from the iliotibial band. During this time, five patients ruptured the ACL in the contralateral knee, and one on the same side. Of the remaining 34 patients, the mean Lysholm score was 97, the IKDC score was normal or near normal in 77%, and 76% of the patients returned to the same level of activity as before injury. Complaints of the appearance of the harvest site were made by 20%, 8% had slight pain during activity due to lateral muscle herniation and problems with staples were common.

A graft from the iliotibial tract has satisfactory mechanical properties and results in less anterior knee pain. However, there is a long lateral operative scar, a risk of herniation of the quadriceps muscle and interference with an important lateral stabiliser of the knee.

Allografts

Animal studies have shown that allografts can be used successfully in intra-articular reconstruction of the knee.⁸⁸⁻⁹⁰

The absence of morbidity at the donor site and the small incisions required for implantation have led to consideration of the use of allograft in reconstruction of the ACL. The most commonly used allografts are the patellar tendon and tendo Achillis, but in the past other tendons and the ACL have been used.

Several studies have compared the results of allografts with autografts in reconstruction of the ACL with no significant difference in knee laxity or outcome.⁹¹⁻⁹⁴ The results of reconstruction with allograft patellar tendon appear to be durable. Noyes and Barber-Westin⁹⁵ found no significant change in knee laxity or in the overall knee score when assessing their patients at three and seven years.

The use of allografts is dependent on an effective process of screening for viral disease. The risk of such infection has been estimated at 1:600 000.⁹⁶ The human immunodeficiency virus can survive freezing and freeze-drying in bone.⁹⁷ The techniques of harvesting, sterilisation and preservation must not damage the graft.

Deep freezing appears to be superior to freeze thawing for preservation of the allograft in that it protects biomechanical properties such as load, stiffness and the modulus of elasticity.^{98,99}

Initially, allografts were secondarily sterilised with ethylene oxide but patients developed delayed toxic and inflammatory reactions followed by failure of the graft.^{56,57} Gamma irradiation is now commonly used to decrease the risk of transmission of disease but it has been shown to affect the tensile properties of the ligament. The tissue morphology is also altered since irradiation separates the collagen fascicles resulting in crimping. These harmful effects have been shown to be minimal with a dosage less than 3 Mrad and therefore 2.5 Mrad is commonly

used.^{100,101} Animal studies have shown that deep-frozen gamma-irradiated ACL allografts have the potential to attain the main biomechanical properties of the normal ACL.^{100,101} Another study¹⁰² has demonstrated a reduction in the ultimate tensile load of fresh-frozen bone-patellar tendon-bone allograft from 2552 N to 1990 N after irradiation of 3 Mrad with a reduction of stiffness from 633 N/m to 531 N/m.

Studies of goat patellar-tendon autograft and allograft suggest that autografts are slightly superior⁸⁹ with more rapid incorporation and slightly better stability six months after operation.

Despite the attractions of no morbidity from harvest of the graft, satisfactory properties and ready availability, the use of allografts is recommended mainly for revision surgery or when multiple grafts are required for complex instabilities.

Synthetic grafts

The use of a synthetic material for ACL reconstruction was first described in 1918 by Alwyn-Smith¹⁰³ who attempted to use silk sutures as a replacement. These failed within three months. Since then numerous attempts have been made to create synthetic ligaments in order to avoid the complications associated with the use of autogenous and allogeneic tissues.

Experience with fully prosthetic grafts has been disappointing. Graft substitutes have been too abrasion-sensitive resulting in rupture and osteolysis. The results have been poor with Gore-Tex grafts,¹⁰⁴⁻¹⁰⁶ Dacron,¹⁰⁷⁻¹¹⁰ carbon fibre^{111,112} and the Leeds-Keio device.¹¹³⁻¹¹⁵

Kennedy et al¹¹⁶ introduced the concept of the ligament augmentation device (LAD) in 1980. This is a flat piece of 6 mm diamond-braided polypropylene, designed to protect the biological graft while it undergoes its phase of degeneration and weakness. Several studies have evaluated the efficacy of the LAD with either hamstring or patellar tendon grafts.¹¹⁷⁻¹¹⁹ None has shown superior results. Fixation of the LAD at both ends can lead to failure of the biological graft as a result of stress shielding.

Collagen-based ligament grafts

Realisation of the limitations of synthetic grafts has stimulated the development of more biologically based scaffolds. Most have collagen matrices derived from demineralised bone or collagen dispersion. They have been used alone or seeded with fibroblasts in an attempt to recreate neoligaments.¹²⁰⁻¹²² The initial results have been encouraging with site-specific remodelling, bone formation in the tibial tunnel, a ligament-like transition zone and an intra-articular region with orientation of the collagen as in a ligament. However, these scaffolds are allogenic and have poor tensile strength, with limited flexibility for modification.

Xenograft, tissue-engineering grafts, growth factors and gene therapy

The early results using xenografts in animal and human studies were disappointing. Apart from showing limited vascular invasion and no ingrowth of host fibrous or osseous tissue, they

also showed extreme intra-articular wear and a high incidence of severe synovitis.^{123,124} An animal study using the extracellular matrix derived from the mucosa of porcine small intestine as a scaffold for replacement of the ACL in the goat showed promising results.¹²⁵ The most recent animal studies of xenograft rejection showed that removal of alpha-Gal epitopes from the xenograft greatly reduced the immune response and was an important first step in decreasing the immune rejection in primates.¹²⁶

Tissue engineering is a multidisciplinary field which merges the technologies of cell and molecular biology, tissue culture, and the material sciences. Research is presently underway to develop biological scaffolds, which are biodegradable constructs seeded with cells. Tissue-engineered ligament grafts may be the future of ACL reconstruction. Animal studies^{127,128} have demonstrated the generation of neoligaments and tendons by implanting polyglycolic acid scaffolds seeded with bovine tendon fibroblasts or fibroblasts isolated from bovine ACL in nude mice models. Gross and histological examination showed tissue with great similarity to normal tendons and ligaments. Composite structures comprising bone and ligament have been developed. Ibarra et al¹²⁹ have described the generation of a bone and ligament construct by seeding two different cell types onto polyglycolic acid scaffolds in nude mice models. These studies demonstrate the potential to generate autologous ACL grafts from patients' own fibroblasts and biodegradable polymer scaffolds.

It is likely that these tissue-engineered ligaments will include growth factors, which accelerate and promote healing of soft tissue. Growth factors are specific signalling molecules which direct changes in the proliferative and migratory behaviour of cells. They may promote revascularisation of the graft and healing of the bone blocks or tendinous tissue to the bone tunnels. This should enable patients to return to work and sport more quickly. The growth factors bone morphogenic protein 13, bone morphogenic protein 7 (OP1), platelet-derived growth factor, transforming growth factor β , epidermal growth factor and basic fibroblast growth factor have been shown to enhance the healing response of ligaments.¹³⁰⁻¹³³ These, however, are hampered by their short half-life and novel techniques are being developed to prolong their delivery. One promising avenue is gene therapy. The required growth factor can be encoded into a denatured viral or non-viral vector, which can invade target cells allowing sustained release of these growth factors. Menetrey et al¹³⁴ have established persistence of a marker gene for up to 42 days in the rabbit ACL, while another study¹³⁵ has demonstrated the presence of a marker gene at the tendon bone tunnel interface in a rabbit model for 21 days.

Summary

Satisfactory and enduring clinical results can be obtained with autografts and, with some reservations regarding

donor screening, harvesting and sterilisation, also with allografts. Some patients are better suited to specific types of graft.

Sports. Evidence of hamstring weakness in flexion after harvesting of the semitendinosus/gracilis³⁰ suggests preference for other grafts in sports such as gymnastics and wrestling. Hamstring tears are common in football and sprinting sports, which may indicate why patellar tendon grafts are the most widely used in these activities.

Patellar tendinopathy is common in basketball and tennis leading some to suggest the avoidance of grafts involving the extensor mechanism in these activities.

Occupation. The most common site for donor site pain following harvest of a patellar tendon graft is over the tibial tubercle. Hence those, such as carpet layers and tilers, whose employment requires kneeling may prefer an alternative graft.

Technical difficulties. The less experienced surgeon may find harvest of the hamstring graft to be technically less demanding than the bone-patellar tendon-bone procedure with easier passage of the smoother graft through the bone tunnel.

Rehabilitation. If difficulties in rehabilitation are anticipated, a hamstring graft requires less supervision with less risk of complications such as the infrapatellar contracture syndrome, arthrofibrosis or persisting pain. However, more rapid incorporation with graft healing to bone is found with the bone-patellar tendon-bone preparations which therefore have more potential for accelerated rehabilitation.

Open growth plate. Animal studies have demonstrated that a drill hole left empty across the growth plate will lead to localised arrest. A drill hole filled with soft tissue will not give rise to a bone bridge and growth may continue.¹³⁶ Several authors^{137,138} have confirmed the safety of hamstring grafts across growth plates in immediately prepubertal and pubertal children.

Hyperextension. A hyperextension injury is a common cause of traumatic failure of an ACL graft. Proprioception appears to be enhanced as a result of dominance of the hamstring relative to the quadriceps.²⁶ In the patients with a tendency to hyperextension a patellar tendon or quadriceps tendon graft is probably preferable.

Rapid return to sport. This issue is controversial and at times seems to defy the scientific data on graft healing and pathological changes. However, in Australian Rules Football, in which a high incidence of ruptures of the ACL occurs, there have been no differences in the time of returning to first-division level when comparing hamstring and patellar tendon grafts.

There is no recommended time for return to high-risk activity. This should be when strength, stability, mobility, proprioception, confidence and technical skills have been adequately rehabilitated.

Cosmesis. Kartus et al¹² have demonstrated a correlation between the size of the scar, sensory loss and anterior knee pain. Allografts have the advantage of minimising the scar

and a hamstring tendon graft probably requires a smaller exposure for harvest than other autografts.

Availability and cost. These become relative factors when considering allografts and synthetics. They may also affect the choice of device for graft fixation and hence the protocol for rehabilitation.

Conclusions

Autografts are selected by most surgeons as the appropriate substitute after rupture of the ACL with allografts having a small but loyal following. The bone-patellar tendon-bone graft has a small lead over the four-strand hamstrings replacement as the most popular autograft. It remains to be seen whether tissue engineered autologous grafts or synthetics or immunologically-treated xenografts will make a significant contribution in the future.

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