Anterior cruciate ligament reconstruction with remnant preservation: current concepts

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ABSTRACT
Anterior cruciate ligament (ACL) tears are a common knee injury, and anatomic ACL reconstruction (ACLR) is now the standard of care to restore knee stability. Nevertheless, re-tear rates exceeding 5% are commonly reported, with an even higher percentage of patients unable to achieve preinjury knee function. As the torn ACL remnant contains elements (eg, cells, blood vessels and mechanoreceptors) essential to ACL function, it has been hypothesised that ACLR with remnant preservation may improve graft remodelling, in turn more quickly and completely restoring ACL structure and function. In this Current Concepts review, we summarise the present understanding of ACLR with remnant preservation, which includes selective bundle reconstruction of partial (one-bundle) ACL tears and single- and double-bundle ACLR with minimal to partial debridement of the torn ACL stump. Reported benefits of remnant preservation include accelerated graft revascularisation and remodelling, improved proprioception, decreased bone tunnel enlargement, individualised anatomic bone tunnel placement, improved objective knee stability and early mechanical support (with selective bundle reconstruction) to healing tissues. However, clinical studies of ACLR with remnant preservation are heterogeneous in the description of remnant characteristics and surgical technique. Presently, there is insufficient evidence to support the superiority of ACLR with remnant preservation over the standard technique. Future studies should better describe the ACL tear pattern, remnant volume, remnant quality and surgical technique. Progress made in understanding and applying remnant preservation may inform, and be reciprocally guided by, ongoing research on ACL repair. The goal of research on ACLR with remnant preservation is not only to achieve anatomic structural restoration of the ACL but also to facilitate biologic healing and regeneration to ensure a more robust and functional graft.

INTRODUCTION
Anterior cruciate ligament (ACL) tears are common, with over 200,000 ACL injuries occurring annually in the USA.123 Despite advances in surgical techniques and rehabilitation protocols, re-tear rates exceeding 5% are commonly reported following ACL reconstruction (ACLR), with an even higher percentage of patients unable to achieve preinjury knee function.4 In response, researchers continue to seek new strategies to better restore ACL structure following injury so as to more fully achieve joint function equivalent to the native knee. As the acutely torn ACL remnant (figure 1) contains elements (eg, cells, blood vessels and mechanoreceptors) essential to ACL function, it was hypothesised that ACLR with remnant preservation may improve graft remodelling, in turn more quickly and completely restoring ACL structure and function, than conventional ACLR techniques in which the torn ACL stump is completely debrided.
inconsistent benefit, but no harm.9–12 Herein, we review the basic and preclinical studies that justify remnant preservation when performing ACLR. Thereafter, the clinical literature is critically appraised to identify potential benefit and inconsistencies across studies, which may guide future research on remnant preservation in ACLR.

**ACLR with remnant preservation**

Remnant preservation defined

The seminal publication by Feagin and Curl demonstrating poor healing and persistent instability following primary ACL repair,13 coupled with the increasing adoption of arthroscopy, ushered in the era of arthroscopic ACLR. During this time, the ‘torn ACL’ was considered mechanically incompetent and its removal inconsequential, or actually necessary, for arthroscopic visualisation during ACLR. However, recent studies demonstrated that up to 25% of ACL ruptures involve only one of the two ACL bundles, and even complete ruptures (ie, both bundle ruptures) can occur at different locations within each bundle.14 15 Techniques for ACLR with remnant preservation reflect this heterogeneity in tear pattern and location. When a single bundle (ie, anteromedial, AM, or posterolateral, PL) is torn, selective AM or PL bundle reconstruction (figure 2) has been achieved by drilling bone tunnels16–18 or using the over-the-top technique.19 Remnant preservation has been performed in both single-bundle20 21 and double-bundle21 22 ACLR. The remnant may be partially debrided or completely preserved (figure 3). Consequently, the term ‘remnant preservation’ used herein remains broadly inclusive but entails retention of some (or all) of the torn ACL stump or an intact (AM or PL) bundle. Under this definition, ACLR with remnant preservation is theorised to accelerate graft remodelling, improve recovery of proprioception, decrease bone tunnel osteolysis, guide anatomic bone tunnel drilling and provide mechanical support to the healing graft in the case of selective bundle reconstruction.

**Graft remodelling**

As the native ACL is both vascularised23 and contains stem/progenitor cells,24 25 remnant preservation has been hypothesised to facilitate graft remodelling through the contribution of these elements. Sun et al8 reported superior vascular density, intratunnel and intra-articular graft integration and biomechanical properties, when the remnant was preserved in a rabbit model. In contrast, Zhang et al7 reported no benefit in cell proliferation and revascularisation while reducing anterior translation (but not improving structural properties of the graft) in a sheep model. In contrast, Takahashi et al4 found that remnant preservation enhanced cell proliferation and revascularisation while reducing anterior translation (but not improving structural properties of the graft) in a sheep model. Investigation of graft revascularisation and maturation in clinical studies has largely relied on MRI correlates, given the obvious barrier to commonly performing histological analyses on human samples. In a prospective randomised study, single-bundle ACLR with a hamstring autograft was performed with either minimal or complete debridement of the infrapatellar fat pad, ligamentum mucosa and ACL remnant, with minimal debridement...
enhancing revascularisation at 2 months and maturation at 6 months. Conversely, when selective bundle reconstruction or double-bundle ACLR was performed with hamstring autografts, remnant preservation did not significantly affect graft maturation. In a systematic review of studies investigating graft maturation following ACLR, Panos et al found that hamstring autografts matured faster than patella tendon autografts, with no additional effect mediated by remnant preservation.

Proprioception
Mechanoreceptors, including Ruffini corpuscles, Pacinian corpuscles, Golgi-like tendon organs and free nerve endings, have been found in the ACL remnant. Whether the noted mechanoreceptors induced neoinervation leading to greater mechanoreceptor density following additional effect mediated by remnant preservation. In a systematic review of studies investigating graft maturation following ACLR, Panos et al found that hamstring autografts matured faster than patella tendon autografts, with no maturation following ACLR, Panos et al. In a study of 10 patients, Matsumoto et al compared double-bundle ACLR with and without suturing of minced autologous remnant tissue to the proximal and distal regions of the hamstring grafts that were then secured in bone tunnels. There was no difference in clinical outcomes between groups, but inclusion of ruptured tissue reduced femoral tunnel enlargement as assessed by CT at 1-year follow-up, suggesting that the minced remnant tissue mediated some anti-catabolic effect at the healing tendon–bone interface. Of note, studies demonstrating remnant-mediated reduction in bone tunnel enlargement have predominantly used soft tissue grafts. Remnant preservation may have less effect with the use of grafts with bone blocks (eg, BPTB), as direct bone-to-bone healing is thought to mitigate the risk for bone tunnel enlargement.

Bone tunnel enlargement
Bone tunnel enlargement is a known phenomenon following ACLR, especially with the use of soft tissue grafts (eg, hamstring tendon vs bone–patellar tendon–bone, BPTB). The aetiology of bone tunnel enlargement is multifactorial and likely includes osteolysis secondary to cytokines contained in the synovial fluid. Remnant preservation may reduce bone tunnel enlargement in part by preventing synovial fluid from extravasating into the bone tunnel. While tunnel enlargement per se was not investigated by Takahashi et al in a sheep model comparing remnant-preserving versus conventional ACLR, the authors reported that remnant preservation did maintain the direct insertion structure of the tibial enthesis. Similar histological analysis has not been performed in human patients. On the other hand, measurement of tunnel enlargement following ACLR has been performed using both radiographs and CT, as reported in numerous clinical studies.

In a prospective randomised study with patients who underwent single-bundle ACLR with quadrupled hamstring tendon autograft, tibial tunnel enlargement was observed in 29.6% of patients in the remnant-preserving group compared with 58.4% of patients in the conventional group. Similarly, the percentage of tibial tunnel enlargement was 25.7±6.7 and 34.0±8.9 in the remnant-preserving and conventional groups, respectively. Both differences were statistically significant. In a related study comparing selective bundle reconstruction against conventional single-bundle ACLR with a hamstring autograft, the former group demonstrated less femoral and tibial tunnel widening, as assessed by radiographs at 2-year follow-up. Yanagisawa et al comparing patients who underwent double-bundle ACLR with hamstring autografts, found that remnant preservation reduced tunnel enlargement in the femoral and tibial tunnels of the AM bundle, but not the PL bundle tunnels. Masuda et al also reported that remnant preservation in anatomic double-bundle ACLR with hamstring autografts reduced tunnel enlargement in the femoral AM tunnel and did not increase the incidence of tunnel coalition. In contrast, Naraoka et al found that remnant preservation did not reduce tibial tunnel enlargement at 1-year postoperatively in a cohort study of double-bundle ACLR with hamstring autografts. Notable to this study, >25% of the intra-articular portion of the native ACL was considered remnant preservation, and ~50% of patients were lost to follow-up due to graft re-rupture and/or the absence of CT scans.

Reduction in tunnel enlargement is one of the more robust effects of remnant preservation, as supported by recent systematic reviews, but the mechanism of this protective effect is unclear. As stated above, prevention of synovial fluid leakage into the bone tunnel may negate the previously reported inhibitory effect of synovial fluid on tendon–bone healing. Additionally, the remnant tissue itself may release paracrine factors that promote tendon–bone integration and/or reduce osteolysis in the bone tunnel. In a pilot study of 10 patients, Matsumoto et al compared double-bundle ACLR with and without suturing of minced autologous remnant tissue to the proximal and distal regions of the hamstring grafts that were then secured in bone tunnels. There was no difference in clinical outcomes between groups, but inclusion of ruptured tissue reduced femoral tunnel enlargement as assessed by CT at 1-year follow-up, suggesting that the minced remnant tissue mediated some anti-catabolic effect at the healing tendon–bone interface. Of note, studies demonstrating remnant-mediated reduction in bone tunnel enlargement have predominantly used soft tissue grafts. Remnant preservation may have less effect with the use of grafts with bone blocks (eg, BPTB), as direct bone-to-bone healing is thought to mitigate the risk for bone tunnel enlargement.

Bone tunnel positioning
As improper bone tunnel positioning is a leading cause of graft failure, the importance of accurate and reproducible tunnel placement is imperative to successful outcomes following ACLR. Anatomic ACLR, with placement of the bone tunnels within the footprint of the native ACL, best restores ACL function and knee kinematics. With emerging evidence that anatomic (vs non-anatomic) ACLR reduces the risk of osteoarthritis. As subtle variation in anatomy is known and expected across individuals, anatomic reconstruction entails individualisation of graft sizes, tunnel positions and fibre orientation. Remnant preservation may guide anatomic bone tunnel placement, in accordance with the individual patient’s unique ACL morphology. Lu et al compared outcomes following double-bundle ACLR with hamstring autografts in which the bone tunnels were drilled in reference to bony landmarks (ie, complete remnant debridement) or the remnant footprint (ie, remnant preservation). As shown on three-dimensional CT, there was greater variability in tunnel positioning in the remnant preservation group. At 3-year follow-up, there was no difference between groups in Tegner or pivot shift scores, but the remnant preservation group showed better functional results with regards to faster range of motion (ROM) recovery, higher subjective outcomes scores (ie, International Knee Documentation Committee [IKDC] and Lysholm) and lower failure rate. This suggested that remnant preservation may facilitate placement of bone tunnels within the native ACL footprint for each individual patient, although alternative mechanisms may explain the benefit of remnant preservation found in this study. On the other hand, remnant preservation does not necessarily involve individualisation. In a related study by Naraoka et al, remnant preservation was categorised as retention of >25% of the native ACL length, with less than <25% constituting the non-remnant group. In this study, remnant preservation did not influence tunnel positioning.
Mechanical support
With advances in medical devices and orthobiologics, there has been renewed interest in ACL repair, despite its history of high failure rates with persistent instability, as compared with ACLR. Clinical use of suture augmentation (eg, internal bracing) to provide early mechanical support to the healing ACL tissue has been informed by animal studies demonstrating compromised healing with primary end-to-end repair alone (absent mechanical support). As the use of suture augmentation in ACLR or ACL repair is mired with reports of high complication rates, the use of suture augmentation, selective bundle reconstruction may provide a preferred, effective alternative for early mechanical support of the healing (torn) bundle, rather than suture augmentation. Clinical studies of selective bundle reconstruction are promising, but the number of studies is small, the level of evidence is low and biomechanical studies elucidating any benefit of bundle preservation are absent.

Clinical outcomes
Despite the advantages of remnant preservation detailed above, the number of clinical studies directly comparing clinical outcomes following ACLR with or without remnant preservation remains relatively small (ie, <10), with modest heterogeneity in study design, surgical technique, follow-up time and outcomes measured. To date, 4 systematic reviews on the topic have been published, each including 6 to 13 primary studies, with variability in inclusion criteria. Tie et al limited their review to randomised controlled trials (RCTs) of single-bundle ACLR with or without remnant preservation. No pooled differences were found between groups in regard to KT arthrometer measurements, negative rates of Lachman, pivot shift test grades, IKDC scores, Lysholm scores or complications. Remnant preservation was found to reduce tibial tunnel enlargement. In a review from the same year, Hu et al included studies with any type of remnant preservation, spanning all levels of evidence, resulting in 13 included studies. Outcome measures were inconsistently performed across studies, from which the authors concluded that short-term clinical outcomes following ACLR with remnant preservation are comparable, if not superior, to the standard technique, but with insufficient evidence to justify its routine use. A 2016 review by Tanabe et al included 10 studies and found that postoperative knee stability was improved by remnant preservation, but only when there was ‘sufficient coverage’ of the graft by remnant tissue. ‘Sufficient coverage’ was not uniform across included studies, with a threshold ranging from >20% to >50% of the native ACL length to constitute adequate remnant preservation. In the most recent systematic review, Wang et al analysed seven RCTs comparing ACLR with or without remnant preservation. Included studies used single- or double-bundle ACLR with autografts or allografts derived from various tissue sources (ie, BPTB, hamstring tendon, tibialis anterior). The meta-analysis found that there were no differences between groups in IKDC scores, complication rates, pivot shift scores or Lachman test grades, but remnant preservation was superior to conventional technique in regards to Lysholm scores and side-to-side (ie, anterior tibial translation) differences. As with all clinical research, studies of long-term outcomes are also needed, but seldom reported. In a prospective RCT with 10-year follow-up by chart review and phone consultation, patients who underwent single-bundle ACLR with remnant preservation reported similar re-tear incidence and perceived knee function as those without remnant preservation. However, the study was limited by a relatively small sample size (n=44 total, n=22 per group) and no further evaluation of objective or subjective knee function.

Complications and potential disadvantages
The risk of cyclops syndrome, a symptomatic extension deficit due to impingement of a cyclops lesion within the intercondylar notch, was thought to be increased by remnant preservation, based on early case series. However, subsequent studies did not support these early concerns. A recent multicentre study including 3633 patients and employing multivariate analysis to identify risk factors for cyclops syndrome following ACLR found that remnant preservation did not predispose to the development of this post-operative complication. Similarly, meta-analyses of remnant-preserving ACLR have not found an increased risk for cyclops lesions, nor any other complication, such as arthrofibrosis or revision. In minimising the debridement of ACL remnant and/or other intra-articular tissues, there is a theoretical risk for compromised visualisation and inaccurate tunnel placement, but this potential disadvantage of remnant-preserving ACLR has not borne out in the literature.

DISCUSSION
One of the greatest impediments to understanding and implementing remnant preservation in ACLR is itself the broad definition of ‘remnant preservation’. Currently, ‘ACLR with remnant preservation’ includes selective bundle reconstruction in partial (ie, one-bundle) tears and single- and double-bundle ACLR with or without partial debridement of the remaining stump. Remnant preservation has been used in ACLR performed with independent or transibial femoral tunnel drilling, with resulting consequences on anatomic versus non-anatomic tunnel placement. Additionally, Crain et al showed that the scar pattern of the ACL stump following injury yields significant differences in knee laxity, with Kirizuki et al showing that CD34+ cells harvested from ACL stumps of these varying tear patterns exhibit different behaviours that may impact healing potential. The volume of remaining ACL tissue that qualifies as a ‘remnant’ also lacks consensus, with detriment to successful application of remnant preservation to ACLR. As an example, Kitamura et al found that the reduction in quantified pivot shift values following anatomic double-bundle ACLR was correlated with the degree of intra-operative graft coverage by preserved remnant tissue. Similarly, Kim et al only found improved graft integrity and synovialisation at second-look arthroscopy when the remnant itself possessed good synovial coverage. As highlighted above, a recent systematic review of ACLR with remnant preservation (vs conventional ACLR) found that larger remnant tissue volumes corresponded with improved measures of objective knee stability. While contradictory examples exist in which greater remnant volume did not further improve clinical or functional outcomes, it is clear that greater description of the tear pattern, remnant volume and remnant quality is needed.

Beyond the torn ACL remnant itself, patient characteristics may also affect the utility of remnant preservation in ACLR. The influence of patient age on outcomes following remnant-preserving ACLR has yet to be explicitly explored, but indirect evidence suggests that patient age may warrant consideration. ACL-derived cells from adolescent patients (age 10–19 years) enhanced tendon–bone healing in a rat model of ACLR to a greater extent than cells from patients aged 30–39 years. As noted above, endogenous cells of the ACL remnant may in part contribute to the presumed benefit of remnant preservation, especially regarding accelerated graft remodelling. Similarly, the
time from injury to surgery may also affect the bioactivity of the remnant cells, as Novarretti et al. 49 found higher expression of ligament-healing factors in remnants from acute (<3 months) versus chronic (>3 months) tears. Shorter times from injury to ACLR may also influence the ability of the preserved remnant to accelerate graft remodelling.69

Much as diligent research over the past two decades has begun to clarify the indications/contraindications for double versus single-bundle ACLR,70 when and how to implement remnant preservation in ACLR will require further research. Presently there is no consensus on when remnant preservation should (or should not) be performed. Progress made in understanding and applying remnant preservation may inform, and be reciprocally guided by, ongoing research on ACL repair. In particular, recent studies demonstrate continued heterogeneity in outcomes following ACL repair.71–74 Much like ACLR with remnant preservation, ACL repair is a promising approach for treating ACL injury but requires further investigation to optimise its implementation.

CONCLUSIONS

Remnant preservation during ACLR may provide several advantages, including accelerated graft remodelling, improved proprioception and decreased bone tunnel widening, but the benefit on clinical outcomes is uncertain. In consideration of the present literature, there is promising but insufficient evidence to support the superiority of ACLR with remnant preservation over the standard technique. Future studies should better describe the ACL tear pattern, remnant volume, remnant quality and surgical technique. Pending further understanding on how and when to apply remnant preservation, anatomic ACLR remains the standard of care for operative treatment of ACL injury.

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