Knee Surg Sports Traumatol Arthrosc (2012) 20:245–251
DOI 10.1007/s00167-011-1565-2

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Why perform an ACL augmentation?

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Received: 19 November 2010 / Accepted: 23 May 2011 / Published online: 9 June 2011

Abstract
Purpose The objective of this article is to determine the importance of an intact anterior cruciate ligament (ACL) stump and its role in the clinical outcome of an ACL reconstruction.
Method A PubMed database search was conducted using the key words "anterior cruciate ligament healing" and "double-bundle structure". Articles concerning ACL healing, reconstruction, and rehabilitation were obtained. A total of 35 studies were incorporated in this article, and factors preset in the intact ACL stump were taken into consideration.
Results Four factors were noted to be important in preserving the stump: protection in early rehabilitation, maintenance of vascular supply, preservation of proprioceptive receptors and may serve as reference for accurate tunnel placement. Also noted was the significance of the intact stump in the natural history, examination, and imaging of such injuries.
Conclusion This study provides a detailed justification in preserving ACL remnants and their vital role in surgical reconstruction of partial anterior cruciate ligament tears.
Level of evidence Therapeutic study, expert opinion with review of Level II-V studies, Level V.

Keywords Anterior cruciate ligament · Partial tear · Healing · Augmentation · Proprioception · Vascularization

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Introduction

A partial tear of the anterior cruciate ligament (ACL) tear is a very common injury. The frequency ranges from 28% according to Noyes et al. [27] and 10–28% according to Jacquot et al. [21] to 35% according to Liljedahl et al. [23]. However, the incidence of a *symptomatic* anteromedial or posterolateral bundle tear is reported to be between 5 and 10% [29, 35].

According to Fruensgaard et al. [18], 50% of partial lesions evolve into complete tears, whereas Noyes et al. [28] put this rate at 38%. Danylchuk et al. [15] reported that partial ACL tears can evolve into complete tears because of the interruption of blood supply, which leads to necrosis of the intact fibers. The amount of initial ligament damage is a statistically significant predictive factor of evolution into complete tear. However, when ACL reconstruction is required, a standard procedure is frequently used, thus sacrificing the residual portion of the ACL.

Many of the previous studies deal with the surgical controversies surrounding ACL management. A particularly critical question is how to deal with partial ACL tears—is it advantageous to preserve the intact bundle and augment it with a graft or is it better to debride the intact stump and proceed with the standard ACL reconstruction technique? In recent years, a lot of scientific articles centered on the treatment of partial ACL tears to answer these questions.

Anatomy

Odenstein et al. initially described the ACL as having fibers that originated from the most anterior part of the insertion area on the tibia inserted on the most medial and proximal part of the insertion area on the lateral femoral condyle, while the fibers originating from the most posterior part of the tibial area inserted on the most lateral and distal part of the femoral area [30]. Further studies showed that the ACL is composed of longitudinally oriented bundles of collagen tissue arranged in fascicular subunits within larger functional bands as described by Siebold et al. [35]. It consists of the anteromedial (AM) and posterolateral (PL) bundle and is separated by a fine septum. The ligament is surrounded by synovium, thus making it extrasynovial. The total length of the ligament is 3 1 ± 3 mm according to Odenstein et al. [30], and the intra-articular length of the AM bundle is in the range of 28–38 mm whereas the shorter PL bundle is an average of 18 mm [20] (Fig. 1).

As stated by McCarty et al. and Miller et al., the primary blood supply to the ligament comes from the middle geniculate artery, which pierces the posterior capsule and enters the intercondylar notch near the femoral attachment [25, 26]. Additional supply comes from the retropatellar fat pad via the inferior medial and lateral geniculate arteries. These sources play a more important role when the ligament is injured. The osseous attachments of the anterior cruciate ligament contribute little to its vascularity.

The posterior articular nerve, a branch of the tibial nerve, innervates the anterior cruciate ligament [25, 26]. Based on Miller et al., histological studies have revealed nerve fibers of the size most consistent with transmitting pain in the intra-fascicular spaces and mechanoreceptors also have been identified on the surface of the ligament, mostly at the insertions of the ligament (especially femoral), below the external synovial sheath [26]. These findings play crucial roles in the rehabilitation of patients with injured anterior cruciate ligaments.

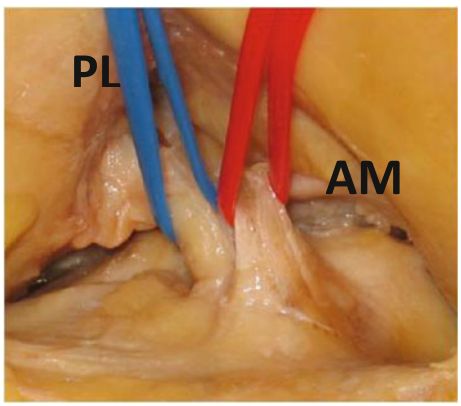

Fig. 1 Cadaveric presentation of the 2 bundles of the anterior cruciate ligament (*AM* anteromedial bundle, *PL* posterolateral bundle)

Biomechanics

According to Miller et al. [26], the anterior cruciate ligament is the primary restraint to anterior tibial displacement, accounting for approximately 85% of the resistance to the anterior drawer test when the knee is at 90° of flexion and neutral rotation [26]. Selective sectioning of the anterior cruciate ligament has shown that the anteromedial band is tight in flexion, providing the primary restraint, whereas the posterolateral portion of this ligament is tight in extension. The posterolateral bundle provides the principal resistance for hyperextension.

According to their distinct insertions sites, each bundle contributes individually to the overall biomechanical function of the ACL. A study by Sakane et al. [31] investigated the specific role of each bundle for anterior stability. The authors showed that the AM bundle has relatively constant levels of in situ forces during knee flexion, whereas the PL bundle is more variable, with high in situ forces at 0°, 15°, and 30° of flexion, but rapidly decreasing thereafter. The AM but especially the PL bundle contributes to rotational stability of the knee in 0°–30° of flexion, and both bundles contribute to anterior stability [31].

In addition to the function as a mechanical restraint to translation, the anterior cruciate ligament has proprioceptive function as evidenced by the presence of mechanoreceptors in the ligament in a study by Adachi et al. [1]. These nerve endings may provide the afferent arc for postural changes of the knee through deformations within the ligament. The exact contributions of the receptors have not been clearly defined.

Patient's history

Partial ACL tears are common injuries that often associate to knee sprains with hemarthrosis. Patients with a symptomatic AM or PL bundle tear usually complain of unspecific symptoms like recurrent pain and swelling as stated by Siebold et al. [35]. More specifically, patients with a symptomatic AM bundle tear describe an anterior instability during activities of daily living and during sports activity similar to a complete ACL tear. On the contrary, patients with a symptomatic PL bundle tear complain of rotational instability with pivoting sports rather than complaining of a significant anterior instability with activities of daily living or sports. Patients with PL bundle injuries only may still perform nonpivoting sports activities without major difficulty, but pivoting sports such as soccer or

basketball have to be given up because of recurrent problems with rotational instability [35].

Physical examination

Based on the current concepts article of Siebold and Fu [35], patients with AM bundle tears usually show a significantly increased anterior drawer test (+1) at 90° of knee flexion. The anterior translation in the Lachman test at 30° is rather small (0 to +1), and the pivot-shift test is negative or only slightly positive (0 to +1) [35]. Patients with AM bundle tears show a KT-1000 side-to-side difference between 2 and 4 mm. On the other hand, patients with PL bundle tears often show a positive pivot-shift test (+1), while the anterior drawer test and the Lachman test may be 0 to +1 as stated by van Eck et al. [38]. KT 1000 measurements of those with PL bundle tears show a small side-to-side difference of 1–3 mm [35].

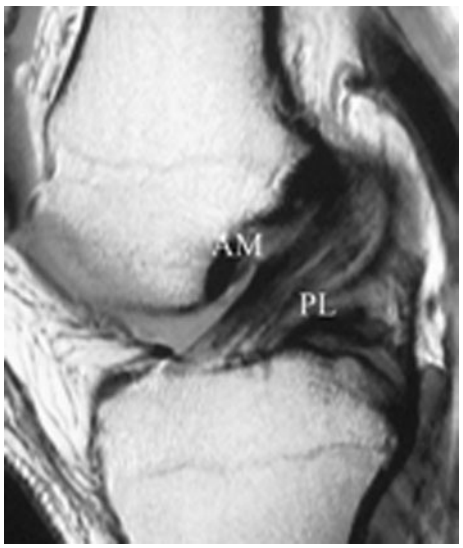

Fig. 2 Magnetic resonance imaging of the knee showing the intact 2 bundles of the anterior cruciate ligament (*AM* anteromedial bundle, *PL* posterolateral bundle)

Imaging

The distinction between partial tear and intact ACL is difficult but Lawrence et al. [22] proposed that thinning of the ligament, a wavy or curved ligament, and a moderate-sized mass posterior to the ligament are features seen more often in the partial tear group. However, the study is retrospective, and the population is small. In addition, the pulse sequences used are not uniform.

According to Siebold and Fu [35], the double-bundle (DB) structure of the intact ACL may be seen on either T1- or T2-weighted 0.2-T MRI on standard views in the sagittal and coronal planes (Fig. 2). However, clear distinction of the 2 bundles is usually very difficult. In most cases, 2 or 3 planes might be necessary to show the specific tear of the AM or PL bundle. A diagnosis on a 1-plane basis usually is not reliable. In the case of an isolated AM or PL bundle tear, the intact bundle may be clearly identified, while the ruptured bundle might be missing. In both instances, the entire picture of the ACL is usually reduced to a significantly thinner structure.

Starman et al. [36] evaluated the intra- and interobserver reliability for assessing the AM and PL bundles using MRI in the axial, coronal, and sagittal viewing planes. They reported that the AM bundle was identified in most standard viewing planes with high frequency and reliability, while detection of the PL bundle was less frequent and had a lower associated reliability. They concluded that it was difficult to reliably detect both bundles using a low-field strength 0.2-T magnet with standard planes of view.

Steckel et al. [37] evaluated the possibility of distinguishing partial ACL tears by dividing the ACL anatomy of 6 cadaver knees in AM and PL bundles and subjecting them to different proton density–weighted fast spin echo sequences. The AM bundle reached a better result in both planes compared with the PL bundle, and the paracoronal plane had a better result in assessing the tear patterns compared with the sagittal plane for the PL bundle. Partial ACL transections could predictably be recognized on oblique sagittal and oblique coronal planes using 3-T MRI technology.

Treatment

Patients with partial ACL tears are generally able to resume activities of daily living and low impact sports after a specific rehabilitation program. Nonoperative treatment often provides unsatisfactory results in highly active patients, and a progression toward complete injury occurs in 12–86% of cases as noted by Noyes et al. [28].

In a study by Buckley et al. [8], they followed up 25 patients with partial ACL tears, who were confirmed arthroscopically and underwent conservative treatment. Follow-up period was a minimum of 18 months. Eight percent of the patients underwent ACL reconstruction due to early deterioration. At the end of the study, 60% had good or excellent results. Only 44% of the patients resumed sports at their pre-injury level. Moreover, 72% had activity-related symptoms.

Bak et al. [5] presented similar findings. They followed up 56 patients with isolated partial ACL tears, who were treated conservatively for a minimum of 5 years. Eleven percent of these patients underwent ACL reconstruction

due to early progression. At the end of the study, 44% had negative Lachman's test and KT-1000 showed none with ≤2 mm side-to-side difference. Sixty-two percent of the subjects had good or excellent knee function; however, only 30% resumed their pre-injury activity level.

In relation to the previously presented researches, a study by Noyes et al. [28] showed that the progression of a partial tear to complete ACL deficiency is related to the estimated extent of the original tear, the presence of any increase in anterior tibial translation, and the occurrence of subsequent reinjury with giving way. Partial tears involving one-fourth or less of the ligament do not frequently progress (12%), whereas tears of one-half or three-fourths do so more often (50 and 86%, respectively). A giving way reinjury was frequent (56%) and more common in athletic activities. This suggests that knees with partial tears are either more prone to subsequent injury or were at greater risk for knee injury. They concluded that surgical reconstruction may often be required (Fig. 3a, b).

Discussion

The most important finding of the study was preserving the intact ACL remnant and doing an augmentation procedure is beneficial to the recovery of an ACL-deficient patient. Based on the review of past and recent literatures, 4 major vital roles of an intact ACL stump in the healing of an anterior cruciate ligament graft were deduced.

First, preservation of the intact remnant guarantees mechanical strength in the early postoperative period, while the graft strength during this period relies primarily on the fixation device. The intact bundle provides protection to the augmentation and hence, may allow faster rehabilitation and earlier return to sports.

Bak et al. assessed the natural history of partial ACL tears 5 years after the initial insult [5]. Seventy-three percent had a negative Lachman test and 27% a +1 or +2 positive Lachman test from the 34 knees examined. Seventy-one percent showed 2 mm or less difference compared with the uninjured knee in terms of instrumental laxity. In this study, however, only 62% had a good-to-excellent knee function, with a significant deterioration in activity noted.

Moreover, Crain et al. examined the anterior laxity using a KT-1000 arthrometer before and after ACL remnant debridement in 48 patients. They found that ACL remnants scarred to the roof of the notch, to the lateral wall of the notch, or to the medial aspect of the lateral femoral condyle aided to the anterior stability of the knee [14]. ACL remnants may serve as biomechanical restraint against anterior translation [14].

In addition, a modeling study of partial ACL injury with simulated KT-2000 tests was done by Lui W et al. in 2002 [24]. A computer model in sagittal plane was designed to replicate different levels of AM and PL bundle tears. Results revealed that the degree of anterior instability was correlated with the amount of partial ACL disruption and the remnants may add to postoperative mechanical stability of the affected knee. Furthermore, in a systematic review by Arneja et al., the authors found no clear trend in the amount of tension applied to the graft during graft fixation [4]. This suggests that initial postoperative stability could be provided by the preserved bundle as to no statistically significant difference has yet been concluded in the previous studies when it comes to immediate stability provided in terms of different amounts of tension applied in grafts.

Second, keeping the intact bundle preserves its blood supply, which may aid in the healing process of the graft. Vascularization may be increased. Odenstein et al. noted uniformly placed connective tissue containing blood vessels in their cadaveric study [30]. Dodds et al. found a vascularized synovial envelope around the ACL and periligamentous vessels penetrating the ligament transversely and anastomosing with a longitudinal network of endoligamentous vessels [16]. Authors also stated that the ends of the ACL have a greater vascular density with the proximal part having greater vascularity compared with the distal portion. In a study by Falconiero et al., they followed up 48 patients and determined the time interval for maturity and remodeling following arthroscopically assisted autogenous

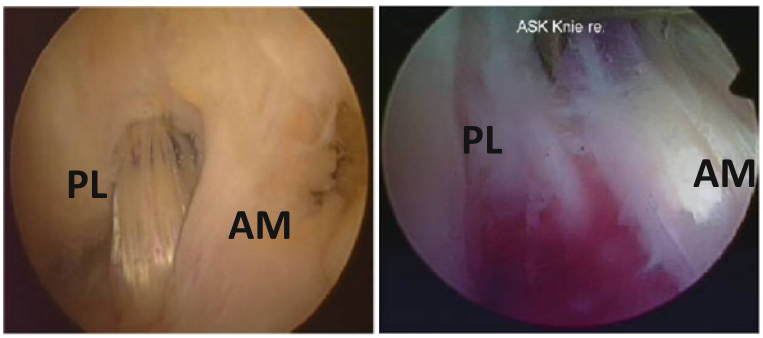

Fig. 3 Arthroscopic images of anterior cruciate ligament augmentation: **a** anteromedial bundle intact with posterolateral bundle augmentation using semitendinosus graft, **b** posterolateral bundle intact with anteromedial bundle augmentation using semitendinosus graft (*AM* anteromedial bundle, *PL* posterolateral bundle)

anterior cruciate ligament reconstruction using biopsy specimens [17]. The authors concluded that revascularization and ligamentization occur over a 12-month period following autogenous ACL reconstruction, with peak maturity evident after 1 year. Also, considering the vascularity and fiber pattern, they showed statistically significant evidence that maturity may occur at an earlier time ranging from 6 to 12 months. Restoration parts of the native ACL tissue may enhance the vascularisation of the augmentation.

Furthermore, in an animal study by Bray et al., ACL in rabbits was dissected and compared with a control group 4 months after a standardized surgically induced partial ACL tear [7]. The results showed significant increase in blood flow and vascular volume in the induced group.

Third, some proprioceptive innervation is maintained with evident benefits for the subjective outcome and for a safer return to sports. The joint position sense may be increased. Schutte et al. in 1987 reported that human ACL is broadly innervated and that neural elements comprise approximately about 1% of the area of the ligament [33]. In a study by Schultz et al., the authors described mechanoreceptors that resemble Golgi tendon organs beneath the synovial membrane of the ACL [32]. Proprioceptive function of the knee has been measured in various ways, such as with the joint position sense test by Co et al. [12] and Corrigan et al. [13] and latency of reflex hamstring contraction by Beard et al. [6]. It has been shown that proprioceptive function in an ACL-deficient knee is less compared with that in a normal knee.

The study by Georgoulis et al. investigated the presence of neural mechanoreceptors in the remnants of the ruptured ACL as a possible source of reinnervation of the ACL autologous graft [19]. They noted free neural ends in all the 17 patients whom the remainder of the torn ACL was selected for histological investigation during ACL reconstruction 3 months to 3.5 years after injury. The authors also stated that if the theory accepts that restoration of proprioception is the result of reinnervation of the ACL, leaving the ACL remnants as a source, may be of potential benefit to the patient. Andersson et al. stated that the ACL contains different sets of mechanoreceptors that provide the central nervous system with afferent information regarding the joint position [3]. Leaving the intact stump preserves the proprioceptive qualities of the native ACL, as stated by van Eck et al. [38].

Adachi et al. measured the correlation between the number of mechanoreceptors and the accuracy of joint position sense in 29 knees and found that proprioceptive function of the ACL is linked to the number of mechanoreceptors [1]. The authors also found mechanoreceptors in patients having a long interval between the ACL injury and the surgery and stated that surgeons should consider preserving ACL remnants during ACL reconstruction.

Lastly, the intact bundle may optimize the accuracy of the procedure by increased arthroscopic orientation and bone tunnel placement at the insertion site. The bundle may serve as a guide for orientation and point of reference for the proper placement of the graft [35].

Conventional ACL reconstructions are often performed, without considering the intact portion of the ACL. In the studies by Buda et al., the surgeons performed ACL reconstruction by sparing the intact bundle of the ACL [9, 10]. The tibial exit point of the tunnel was always found in the anatomical footprint of the bundle to be reconstructed, but the femoral orientation of the graft was anatomical only in case of AMB reconstruction, while in case of PLB reconstruction it was more vertical. The authors described a technique for ACL augmentation with quadrupled distally inserted hamstrings with an over-the-top fixation, preserving the residual portion of the ACL. This technique was shown to provide excellent clinical results. In another study by Serrano-Fernandez et al., the authors described a surgical augmentation technique that uses an over-the-top fixation. Based on their results, they concluded that addressing both bundles of the ACL provides better rotational stability and thus, suggesting preserving the intact bundle and reconstructing only the torn bundle [34]. Moreover, Camarda et al. recommended drilling the PLB tunnel through a low accessory AM portal at high knee flexion [11].

In addition, Adachi et al. compared 40 patients in which they performed a selective reconstruction of the AM or PL bundles to a group of patients with complete ACL reconstruction [2]. The ACL augmentation group showed significantly better anteroposterior stability and terminal stiffness than the ACL reconstruction group. Siebold and Fu's preliminary results [35] showed good clinical results for AM and PL bundle augmentation at an average of 1 year postoperatively. The objective and subjective IKDC, Cincinnati Knee Score, and the KT-1000 increased significantly from preoperatively to follow-up in all patients [35].

The study is a collaboration of past literatures and is aimed to provide reason in preservation of the intact ACL stump. The level of evidence of the different articles ranged from I to V; hence, the ability to form concrete conclusions in this study is limited by the heterogeneity of the articles used. Specifically, there is significant diversity in the subjects, surgical procedure, and rehabilitation protocols in the different studies cited. A prospective randomised controlled trial comparing ACL reconstruction with ACL augmentation may be necessary to identify that the different factors stated may provide more meaningful conclusions in the future. As for the present, these factors

may well be considered in ACL surgeries and provide surgeons with reasons in preserving intact ACL stumps.

Conclusion

Based on the anatomic and biomechanical double-bundle concept, researches have recently focused on the diagnosis and treatment of symptomatic partial ACL tears. The diagnosis of symptomatic AM or PL bundle tear is a combination of the patient's history and complaints, clinical examination, MRI, and arthroscopic evaluation. The ACL augmentation is performed similar to a "traditional" single-bundle technique while sparing the intact ACL fibers. It may have require a more systematic and accurate placement of portals, but several factors may support preserving the intact ACL stump instead of debriding it. These include increased mechanical stability, increased revascularisation, increased proprioceptive innervation, possibly better orientation of the graft, faster remodeling of the ACL construct and most especially, faster and easier rehabilitation for the patient. As stated by Noyes et al. [28], success after ACL reconstruction may depend not only on the tightness or strength of the reconstruction but also on the quality of recovery of proprioception."We therefore recommend saving as much intact anterior cruciate ligament as possible when performing anterior cruciate ligament surgery.

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