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Outcomes of revision anterior cruciate ligament reconstruction secondary to reamer-irrigator-aspirator harvested bone grafting

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ABSTRACT

Introduction: Patients with widened or misplaced tunnels may require bone grafting prior to revision anterior cruciate ligament (ACL) reconstruction. Utilising reamer-irrigator-aspirator (RIA) harvested bone from the femur showed promising filling rates. Nevertheless, the procedure has neither been validated in a larger population nor been assessed with regards to radiological and clinical outcome of the subsequently conducted revision ACL reconstruction. Therefore, the aim of this study was to evaluate tunnel filling rates, positioning of the revision tunnels and outcome parameters of such two-staged revision ACL reconstructions.

Material and methods: A total of 15 consecutive patients were prospectively enrolled in this case series. CT scans were analysed before and after autologous RIA harvested bone grafting. Tunnel volumes and filling rates were calculated based on manual segmentation of axial CT scans. Revision ACL reconstruction was carried out after a mean interval of 6.2 months (±3.7) and positioning of the revision tunnels was assessed by plane radiographs. The mean follow-up was 19.8 months (±8.4) for objective evaluation and 37.1 months (±15.4) for patient reported outcomes. The clinical outcome was assessed by the quantification of the anterior tibial translation, the IKDC objective score, the Tegner activity scale and the Lysholm score.

Results: Initial CT scans revealed mean tunnel volumes of 3.8cm^3 (±2.7) femoral and 6.1cm^3 (±2.4) tibial. Filling rates of 76.1% (±12.4) femoral and 87.4% (±5.9) tibial were achieved. Postoperative radiographs revealed significantly improved tunnel positioning with anatomical placement in all but one case at the femur and in all cases at the tibia. At follow up, patients showed significantly improved anterior tibial translations with residual side-to-side differences of 1.7 mm (±0.8) and significantly improved IKDC objective scores. Furthermore, significantly higher values were achieved on the Tegner activity scale (5.3 ± 1.4 vs. 2.8 ± 0.5) and the Lysholm score (85.4 ± 7.9 vs. 62.5 ± 10.5) compared to the preoperative status.

Conclusion: Autologous RIA harvested bone grafting ensures sufficient bone stock consolidation allowing for anatomical tunnel placement of the subsequently conducted revision ACL reconstruction. The two-staged procedure reliably restores stability and provides satisfying subjective and objective outcomes. Thus, RIA harvested bone grafting is an eligible alternative to autologous iliac crest or allogenic bone grafting.

Introduction

Anterior cruciate ligament (ACL) ruptures occur at an incidence of up to 60.9 per 100,000 person-years [1,2] and often result in anteroposterior and rotational instability of the knee. Arthroscopic ACL reconstruction is the gold standard for patients with

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symptomatic instability wishing to return to pivoting and cutting sports. It is one of the most commonly performed knee procedures today and the incidence is continuously rising [3]. ACL reconstruction allows for the successful restoration of knee stability and good clinical outcomes in a clear majority of patients [4]. Nevertheless, revision rates of 4.1–20 percent have been reported [5–7]. With more primary ACL reconstructions being conducted, the number of revision ACL procedures increases accordingly. Traumatic reinjuries, technical errors or lacking graft incorporations account for persisting or recurrent instabilities [4,8]. In many cases a combination of all three is evident. As misplacement of tunnels at the primary reconstruction procedure is relatively common, more emphasis should be made on proper training of the surgeons carrying out the initial reconstruction. But beyond that, the utmost care has to be taken when treating revision cases. Revision ACL reconstruction is a technically demanding procedure that requires detailed analyses and accurate planning. Like in primary ACL reconstruction, the goal in revision ACL reconstruction is the fixation of an appropriate graft in good quality bone and anatomically positioned tunnels. In general, preexisting anatomically positioned tunnels can thereby be reused in a one-stage procedure. But if the preexisting tunnels exceed a diameter of 12 mm, sufficient graft fixation is increasingly difficult to achieve. And if the preexisting tunnels are positioned partially extra-anatomically, they converge with revision tunnels positioned anatomically, once again compromising sufficient graft fixation [9,10]. Thus, critical widening or malpositioning of the preexisting tunnels can necessitate a two-staged procedure. In these cases, the removal of the old graft and interfering implants is accomplished in the first stage. In addition, the sclerotic walls of the preexisting tunnels are excavated to vital cancellous bone and the bone grafting is conducted. After a few months, when proper incorporation of the grafted bone can be verified, the actual revision ACL reconstruction can be performed. To date, the bone graft is predominantly harvested at the iliac crest or the proximal tibia [11–15]. Unfortunately, both donor sites feature specific disadvantages. Bone harvesting at the iliac crest is associated with relevant donor-site morbidity in over 20 percent [16] and the quantity of cancellous bone at both sites is limited [15].

In a previously published pilot study, the intramedullary canal of the ipsilateral femur was introduced as an alternative donor site for two-staged revision ACL reconstruction. Using a reamer-irrigator-aspirator (RIA), sufficient amounts of cancellous bone could be harvested. The bone grafting procedure was conducted arthroscopically assisted in a minimal-invasive technique. Computer tomography (CT) analyses after a few months and the subsequently conducted revision ACL reconstruction revealed a high-quality bone stock allowing for sufficient fixation of the hamstring or bone-tendon-bone revision graft [17]. Recently, several studies have been published favouring intramedullary RIA bone grafting over the iliac crest for other orthopaedic procedures. The donor site morbidity is reported to be significantly lower while twice as much or more volume of cancellous bone can be grafted [18–21]. The grafted bone not only consists of extracellular matrix but also of mesenchymal stem cells (MSC), the cellular source of new bone formation. In vitro experiments revealed that RIA-MSC seem to undergo osteogenesis at a faster rate and may have higher differentiation capacities towards osteoblasts than iliac crest MSC [22–25]. Furthermore, in vivo experiments showed RIA-MSC forming twice as much new bone compared to MSC derived from the iliac crest [26].

Nonetheless, the clinical significance of RIA bone grafting procedures has not been assessed with regards to outcomes after the subsequently conducted revision ACL reconstruction. Therefore, the goal of the present study was to follow up on the patients analysing subjective and objective outcome parameters. Special attention has thereby been drawn to answer the following questions:

1 Can the promising filling rates revealed by CT scans in the previously published pilot study be confirmed in a larger population?
2 Does the RIA bone grafting procedure reliably allow for anatomical tunnel positioning in the subsequently conducted revision ACL reconstruction?
3 Does the two-staged procedure sufficiently restore the knee's stability and function?

Materials and methods

Between January 2013 and December 2015, a total number of 15 consecutive patients with an indication for a two-staged revision ACL reconstruction were prospectively enrolled in this case series. The indication was given due to partial extra-anatomically positioned or critically widened tunnels in all cases. A partly extra-anatomically positioned tunnel was at hand when the intended anatomically positioned revision tunnel and the preexisting tunnel were supposed to converge to a larger tunnel. A critical tunnel widening was defined as a maximum tunnel diameter exceeding 14 mm, anticipating the stripping of the sclerotic walls. Under both conditions, bone grafting is required prior to the actual revision ACL reconstruction as sufficient fixation of the tendon graft cannot be ensured otherwise. The study was carried out according to the Declaration of Helsinki. The ethic committee of the University of Munich approved the study under the running ID number 298-2012. All patients gave their written consent to participate in this study.

CT analyses of the preexisting tunnels

In terms of the diagnostic routine in recurrent or persistent instability after ACL reconstruction, CT analyses of tunnel placement and maximum width were conducted in all cases. The data from the CT scans were exported to OsiriX® DICOM Viewer V8.0 and processed into 3D surface models. The femoral tunnel position was assessed after digitally subtracting the medial femoral condyle and by using a true mediolateral view. The tibial tunnel position was assessed after digitally subtracting the femur and by using a craniocaudal view. The centre of the femoral tunnel was measured according to the grid method as initially described by Bernard et Hertel [27] and introduced to 3D CT models by others [28,29]. In a comparable manner, the centre of the tibial tunnel was determined in a rectangular measurement frame drawn over the craniocaudal view of the proximal tibia as described by Lertwanich et al. [29] and Sadoghi et al. [30]. The frame is tangent to the posterior articular margins of both medial and lateral tibial condyles, to the most anterior articular margin of the medial tibial condyle and to the medial and lateral margins of the articular surface. Values are given as percentage of the total distance from deep-to-shallow and from high-to-low for the femoral tunnel as well as from anterior-to-posterior and from medial-to-lateral for the tibial tunnel. Tunnels were considered anatomical when the centre of the aperture was inside a 10 percentage point margin around the following insertion points [30]: 24,8% deep-to-shallow and 28,5% high-to-low at the femur [27] and 43,3% anterior-to-posterior [31] as well as 47% medial-to-lateral [32,33] at the tibia (Fig. 1). The distance between the actual and the anatomical aperture centre were determined as percentage point values. Maximum femoral and tibial tunnel diameters were determined measuring the largest diameter at

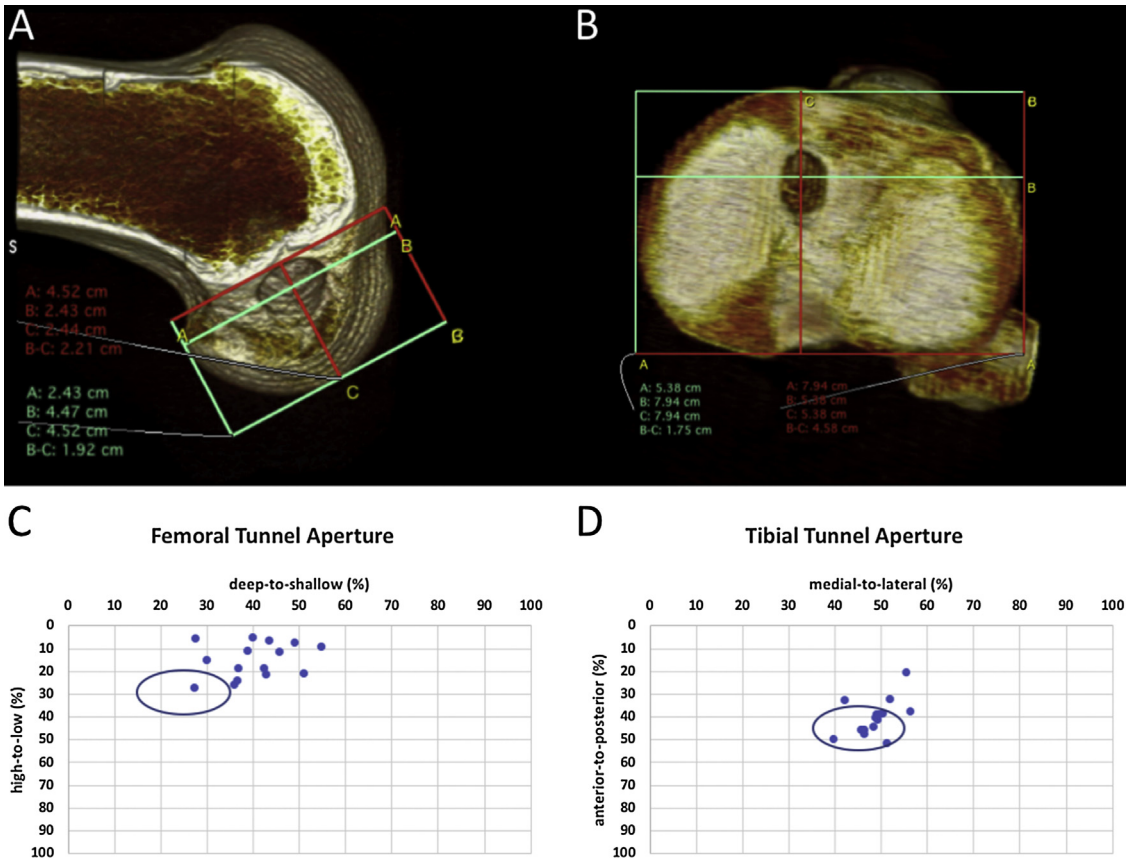

Fig. 1. Analyses of preexisting tunnel positioning 3D reconstructions of the lateral femoral condyle and the tibial joint surface were generated. The position of the femoral (A) and tibial tunnel apertures (B) were determined. The graphs demonstrate the positioning of the preexisting tunnels in reference to the anatomic insertion surrounded by a ten percentage points margin (C, D).

right angles to the tunnel axis on the sagittal, coronal or axial planes (Fig. 2). In cases of preexisting double bundle tunnels and for the purpose of this study, both tunnel volumes were added, the largest diameter of both tunnels was taken and the distance between both tunnel apertures was cut in half to define the arithmetical tunnel aperture.

First stage surgery: Bone grafting procedure

Patients underwent general anaesthesia and were placed in a supine position. RIA cancellous bone grafting was performed as previously described [17,34,35]. In brief, an antegrade approach to the ipsilateral femur was established via a small incision and blunt

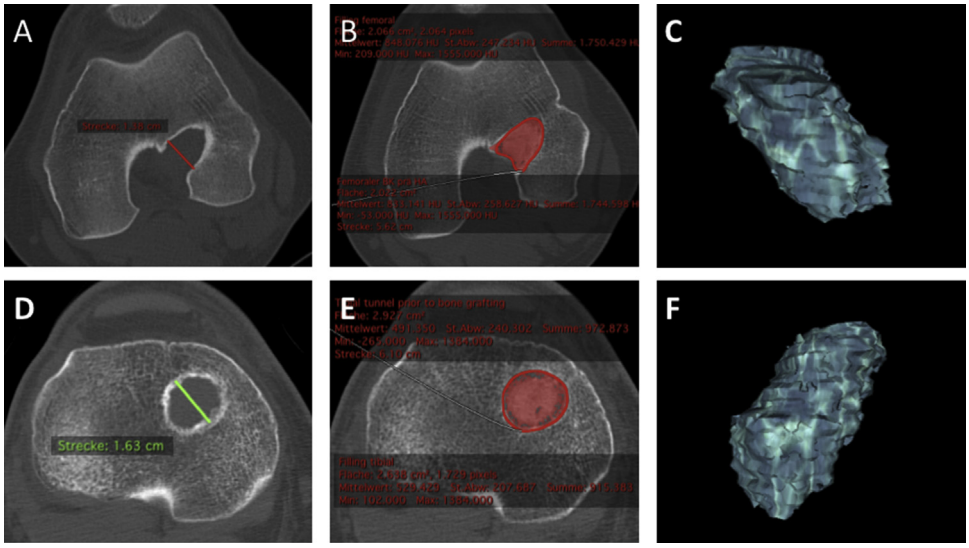

Fig. 2. Dimensions of the preexisting tunnels and filling results after autologous bone grafting as revealed by CT scans. Maximum diameter and volume of the preexisting femoral (A, C) and tibial tunnels (D, F) were determined. Based on the postoperative CT scan, the volumes of the grafted bone and subsequently the filling rates were calculated for the femoral (B) and the tibial tunnel (E).

dissection. A Kirschner wire was introduced to the medullary canal of the femur and the positioning was fluoroscopically checked on two planes. The cortical bone was penetrated using a cannulated drill bit. After the removal of the Kirschner wire, a 2.5 mm guide wire with a ball tip was advanced into the canal. The width of the femoral isthmus was determined using the fluoroscopic gauge. The actual RIA procedure was carried out utilising a corresponding RIA reaming head diameter and under fluoroscopic control. Once sufficient amounts of cancellous bone were harvested, the device was removed, and wound closure was conducted. Proceeding with the arthroscopic procedure, exsanguination was generated, and a sterile tourniquet was inflated to 250 mmHg. The arthroscopy was conducted with the leg being supported horizontally and using a mounted step for support in 90° flexion. The arthroscopic portals and the approach to the distal entry of the tibial tunnel of the initial surgery were reestablished. Meniscal lesions were treated, and chondral lesions were shaven and debrided whenever indicated. Remains of the ACL graft were removed wherever present and both tunnels were identified. Washers or staples were removed, screws were exposed and removed with a screw driver whenever possible. In case of advanced degradation of bio-absorbable screws, guide wires were placed, and the screws were drilled over. All soft tissues were debrided inside the tunnels and special care was taken to entirely remove the sclerotic walls, either by introducing cannulated drill bits with gradual increasing head diameters or by utilizing an arthroscopic burr. Once visualisation of both tunnels revealed healthy cancellous bone at the entire circumferences, the arthroscopically-assisted bone grafting procedure was carried out using cones and push rods as published earlier [17]. Both tunnels were filled with grafted bone retrograde, repeatedly compressing the cancellous bone mass. A rasp was introduced via the anteromedial portal ensuring closure of the proximal entry of the tibial tunnel and avoiding trespassing of bone graft into the knee joint. After sufficient filling of both tunnels, instruments were removed, and wound closure was conducted. After the bone grafting procedure, the patients were mobilised on crutches for two weeks and then admonished to bear full weight but to avoid cutting and pivoting stress.

CT analyses after the bone grafting procedure

After an interval of at least three months, the postoperative CT analyses were conducted. The filling rates were quantified as described before [17]. In brief, thin-sliced CT data sets were exported to OsiriX® DICOM Viewer V8.0 and further processed. First, the tunnel volume prior to the bone grafting procedure (V_1) was determined. Manual segmentations of the femoral and the tibial tunnel were carried out in the axial view and over the entire tunnel lengths. The tunnel outlines on every single slice were manually marked using the pencil tool defining the region of interest (ROI). Based on these ROI, the tunnel volume was calculated. Second, the tunnel volumes after the bone grafting procedure (V_2) were recalculated after setting a threshold of Hounsfield units (HU) (Fig. 2). According to the word of Tie et al. [36], a threshold of 200 and 100 HU was set for the femoral and the tibial tunnel, respectively. The filling rate was calculated as percentage ((V_2/V_1)*100). Additionally, the mean density of the grafted bone was determined in HU.

Second stage surgery: revision ACL reconstruction

The revision ACL reconstruction was conducted using standard set-up and in a traditional anteromedial portal drilling technique. Anatomic tunnel positioning was aspired in all cases. The ACL revision reconstruction was achieved utilising contralateral autologous hamstring grafts, ipsilateral autologous bone-patellar tendon-bone or quadriceps tendon grafts, or allogenic bone-patellar tendon-bone grafts. Fixation of the hamstring grafts was conducted using cortical button at the femur (ACL TightRope RT, Arthrex, Naples, FL.) and bio-absorbable screws (BioRCI, Smith and Nephew, London, United Kingdom), fixation of the bone-patellar tendon-bone grafts was conducted using titanium screws (Mega-Fix-T, Storz, Tuttlingen, Germany).

Radiographic assessment of revision ACL tunnel placement

The accordance of the tunnel apertures with the anatomical insertion areas as well as the tunnel and the graft inclinations were analysed on the plane sagittal and coronal radiographs conducted postoperatively. Tunnel positions were considered anatomic when the centre of the tunnel aperture met the femoral and tibial insertion defined previously [27,31–33]. Again, a deviation of ten percentage point was tolerated [30] (Fig. 3). Femoral and tibial tunnel inclination were determined measuring the angle of the central line of best fit to the horizontal or vertical. The axial inclination of the femoral tunnel was trigonometrically calculated as a tangent (tan) function of the sagittal and coronal inclination. The axial inclination of the femoral tunnel assesses the clock face orientation applied intraoperatively. Approximatively representing the ACL-graft inclination, the coronal femoral tunnel-tibial tunnel obliquity was measured according to the method published by the MARS group [37]. The sagittal femoral tunnel-tibial tunnel obliquity was determined adapting the MRI-based method of Illingworth et al. [38]. The tibial horizontal was generated as described, then a second line was drawn connecting the centres of the tibial and the femoral aperture and the resulting inclination angle was measured (Supp. Fig. 1).

Clinical outcome

The objective evaluations were performed prior to the first stage procedure and at the final clinical presentation of the patient, which was at least 12 months after the second stage procedure. The objective evaluations included a thorough clinical examination of both knees, the quantification of the anterior tibial translation as revealed by the Rolimeter measuring gauge (Aircast, Summit, NJ) in comparison to the contralateral side and an assessment according to the 2000 International Knee Documentation Committee (IKDC) Form. The subjective evaluations were conducted prior to the first stage procedure and in terms of a final survey, at least 24 months after the second stage procedure. The subjective evaluations were carried out with patient-based questionnaires utilising the Tegner Activity Scale and the Lysholm Score.

Statistical analyses

Metric results are given as means with standard deviations. Statistical analyses were performed using parametric and non-parametric tests. The chi-square test was used for the nominal results of the IKDC form. Unpaired t-tests were conducted for the metric results of the Rolimeter side-to-side difference, the Tegner Activity Scale and the Lysholm Score. Statistical analyses were conducted with the SPSS software package version 10.0, the probability level was set at $p \leq 0.05$.

Results

The mean patient age at the first stage procedure was 29.5 years (SD ± 6.2). Eight patients were male and seven were female. CT scans before and after the first stage procedures were analysed in all 15 patients. One patient refused to undergo the second stage procedure for personal reasons. Postoperative X-rays after the

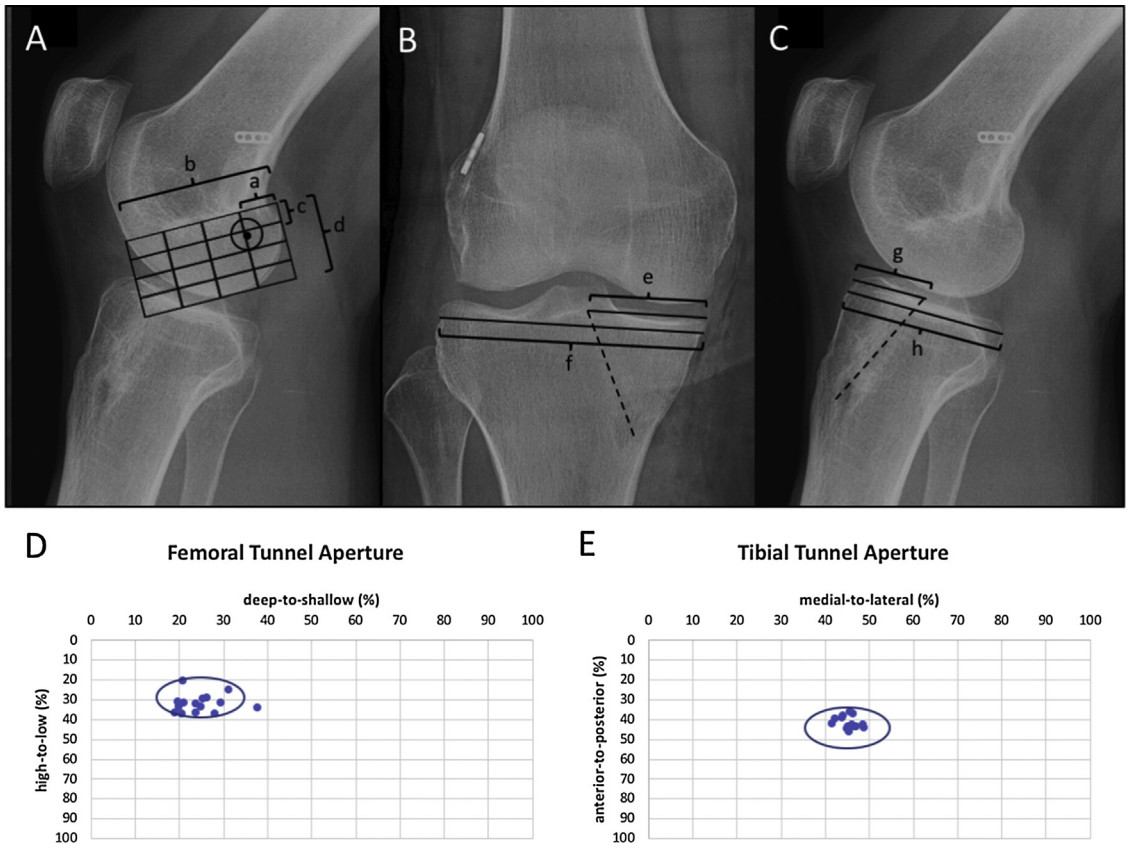

Fig. 3. Radiologic assessment of the revision ACL tunnel positioning. Based on postoperative X-rays, the apertures of the femoral (A) and the tibial tunnel (B, C) were determined. The graphs demonstrate the positioning of the revision ACL tunnels in reference to the anatomic insertion surrounded by a ten percentage points margin (D, E). The positioning of the revison ACL tunnels was significantly better compared to the positioning of the preexisting tunnels ($p < 0.001$ at femur and $p = 0.01$ at the tibia).

second stage procedure were analysed in the remaining 14 patients.

Positions, widths and volumes of the preexisting tunnels

CT analyses of the preexisting tunnels revealed a mean tunnel volume of 3.8 cm^3 (SD ± 2.7) and a mean maximum diameter of 13.9 mm (SD ± 3.3) femoral as well as a mean tunnel volume of 6.1 cm^3 (SD ± 2.4) and a mean maximum diameter of 15.0 mm (SD ± 2.9) tibial. At the femur, the preexisting tunnel was positioned anatomically in one case but exceeded a critical tunnel diameter. At the tibia, the preexisting tunnels were positioned anatomically in 11 cases, thereof the maximum tunnel width exceeded a critical diameter in nine patients (Fig. 1). An anatomically positioned tunnel exceeding a critical width was one of the indications justifying a two-staged procedure. A partly extra-anatomically positioned tunnel, even though not necessarily exceeding a critical width, was the other indication for the two-staged procedure. If the femoral tunnel was positioned completely extra-anatomically, meaning it would not interfere with an anatomically planed revision tunnel, the bone grafting procedure was conducted to the surgeon's preference. In one case, no bone grafting of the femoral tunnel was conducted, and implants were left in place, while the critical width of the tibial tunnel justified the two-stage procedure.

Tunnel filling rates after the first stage procedure

After a mean interval of 4.6 months (SD ± 1.3), CT analyses revealed a mean filling rate of 76.1% (SD ± 12.4) at the femur and of 87.4% (SD ± 5.9) at the tibia. The grafted bone at the femoral tunnel featured a mean volume of 3.0 cm^3 (SD ± 2.0) and a mean density of 574.0 HU (SD ± 137.5). At the tibial tunnel, the mean graft volume was 5.3 cm^3 (SD ± 2.0) and the mean density was 516.7 HU (SD ± 85.8) (Table 1). The difference in mean density of the grafted bone at the femur and the tibia was revealed not to be significant ($p = 0.12$).

Revision ACL reconstruction

The second stage procedure was conducted after a mean interval of 6.2 months (SD ± 3.7) secondary to the bone grafting procedure. Contralateral autologous hamstring grafts were utilized in seven patients, ipsilateral autologous bone-patellar tendon-bone or quadriceps tendon grafts were used in four patients, and allogenic bone-patellar tendon-bone grafts were implanted in three patients.

Revision tunnel positioning

After the second stage procedure, postoperative plane radiographs were taken in all 14 cases. Applying the quadrant method to the lateral view revealed the centre of the femoral tunnel aperture projecting onto a mean depth of 25.5% (SD ± 5.6) and a mean height and of 31.8% (SD ± 5.0). The previously defined criteria of an anatomical tunnel positioning were fulfilled in 13 out of 14 patients. The centres of the preexisting femoral tunnel apertures featured a mean deviation of 21.2 percentage points (SD ± 9.2) from the anatomic insertion point. The centres of the femoral revision ACL tunnel apertures showed a mean deviation of 7.4 percentage points (SD ± 3.1). This improvement in femoral tunnel positioning was statistically significant ($p < 0.001$). The centre of

Table 1
Dimensions of the preexisting tunnels and filling results after autologous bone grafting as revealed by CT scans. The ratio of preexisting tunnel volumes and the occupying volumes of the grafted cancellous bone yielded in the filling rates. SD standard deviation.

	femoral				*tibial*			
	max. diameter (mm)	tunnel volume V_1 (ccm)	grafted bone volume V_2 (ccm)	filling rate (%)	max. diameter (mm)	tunnel volume V_1 (ccm)	grafted bone volume V_2 (ccm)	filling rate (%)
1	12.2	2.1	1.3	61.9	16.0	6.6	6.2	92.9
2	11.5	4.1	2.5	60.7	11.2	3.3	3.1	93.0
3	10.0	2.9	1.9	65.5	10.5	3.7	3.5	95.1
4	13.4	5.3	3.9	73.8	15.1	6.1	5.4	88.0
5	18.4	10.1	7.9	77.9	20.5	12.9	11.0	85.3
6	23.1	9.7	6.2	64.3	18.3	7.2	5.6	78.2
7	16.0	4.7	4.4	92.6	16.3	6.6	5.9	89.2
8	13.4	2.5	2.2	85.0	13.6	4.2	3.4	80.8
9	13.2	4.0	2.9	73.0	15.7	5.6	5.0	89.8
10	11.5	1.3	1.0	73.8	12.1	6.8	5.6	81.6
11	11.3	2.1	1.4	65.2	16.8	7.9	7.2	90.5
12	15.8	3.0	2.4	79.7	15.9	6.3	5.3	84.6
13	13.0	2.3	2.1	92.6	18.0	6.2	4.8	76.6
14	12.0	1.2	n/a	n/a	12.5	5.9	5.4	90.8
15	14.3	2.3	2.3	99.1	12.5	2.4	2.3	93.8
mean	**13.9**	**3.8**	**3.0**	**76.1**	**15.0**	**6.1**	**5.3**	**87.4**
SD	**3.3**	**2.7**	**2.0**	**12.4**	**2.9**	**2.4**	**2.0**	**5.9**

the tibial aperture met a mean of 45.7% (SD ± 2.0) measured from medial to lateral using the coronal view and a mean of 42.9% (SD ± 2.7) measured from anterior to posterior on the sagital view. The criteria of an anatomical tunnel positioning were fulfilled in all cases (Fig. 3, Supp. Table 1). The centres of the preexisting tibial tunnel apertures featured a mean deviation of 7.7 percentage points (SD ± 5.9) from the anatomic insertion point. The centres of the tibial revision ACL tunnel apertures showed a mean deviation of 3.0 percentage points (SD ± 2.0). This improvement in tibial tunnel positioning was also statistically significant ($p = 0.01$). The mean inclinations of the revision tunnels and the revision ACL grafts are presented in the supplementary Table 1.

Clinical outcome

After the second stage procedure, one patient living abroad was lost to follow-up. One patient suffered a traumatic rerupture after the revision ACL reconstruction, which was counted as failure but not subjected to further detailed analysis. A total of twelve patients completed the follow-up. The mean follow-up for the objective evaluation after the second stage procedure was 19.8 months (SD ± 8.4). Prior to the two-staged revision ACL reconstruction the mean anterior tibial translation was 12.1 mm (SD ± 1.4). On follow-up, the patients showed a significantly improved translation of 7.7 mm (SD ± 1.4, $p < 0.001$) in the operated knee compared to 6.0 mm (SD ± 0.6) in the healthy knee. The IKDC objective score also significantly improved comparing the status prior to the two-staged revision (A = 0, B = 1, C = 9 and D = 2) with the final follow-up (A = 6, B = 5, C = 1 and D = 0; $p = 0.001$, Fig. 4). The mean follow-up for the for the patient reported outcome after the second stage procedure was 37.1 months (SD ± 15.4). On follow-up, the Tegner Activity Scale revealed a mean score of 5.3 (SD ± 1.4) compared to 2.8 (SD ± 0.5) prior to the two-staged revision. The Lysholm Score increased form a mean of 62.5 points (SD ± 10.5) to 85.4 points (SD ± 7.9) on follow-up. The improvement in both assessments was statistically significant ($p < 0.001$).

Discussion

Anatomical reconstruction should be the primary goal in any revision ACL reconstruction. To this end, the sufficient and dependable tunnel filling is a crucial prerequisite when treating patients with critically widened and partially extra-anatomical preexisting tunnels. The introduction of RIA harvested autologous cancellous bone grafting to two-staged revision ACL reconstruction demonstrated promising filling rates in CT scans of five patients. This previously published pilot study showed mean filling rates of 74.7% femoral and 94.2% tibial [17]. One aim of the present study was to validate these results in a larger population by analysing femoral and tibial tunnel filling rates in 15 consecutive patients. The present validation revealed comparably high filling rates of 76.1% (SD ± 12.4) femoral and 87.4% (SD ± 5.9) tibial. Especially the low standard deviation at the tibial tunnel indicates consistency and reliability of the procedure. Numerous studies have been published on other bone grafting procedures addressing enlarged or misplaced tunnels [11,12,14,15,39–42], but only very few systematically investigate the actual tunnel filling rates. Van Recum et al. achieved filling rates of 83% (SD ± 10) and 78% (SD ± 14) for the femoral and tibial tunnel using autologous bone harvested from the iliac crest. The study also evaluated the filling rates after grafting silicate-substituted calcium phosphate and reported of 88% (SD ± 22) for femoral and 86% (SD ± 17) for tibial [39]. Unfortunately, the study only evaluated radiologic and histologic findings after the first stage procedure and did not asses the success of the actual revision ACL reconstruction or the patients' clinical outcomes. Uchida et al. aimed to only fill a predefined section of the preexisting tunnels. From the intra-articular aperture to a minimum depth of 15 mm, the voids were filled with bone cylinders harvested from the iliac crest [41]. The filling rates were determined in these predefined sections only, where values of 93.8% (SD ± 3.5) were achieved. Uchida et al. followed up on eight of their patients after the revision ACL construction and reported an excellent stability and function two years after the second step procedure. Another finding of the present study were the unphysiologically high density values of the grafted bone. After a mean interval of 4.6 months (SD ± 1.3) following the grafting procedure, the density averaged 574.0 HU (SD ± 137.5) and 516.7 HU (SD ± 85.8) compared to the physiological density in those areas specified with 200 and 100 HU for the femur and the tibia, respectively [36]. The higher density values are presumable due to the successive compression of the RIA harvested cancellous bone. Furthermore, it seems to be a well-known phenomenon as grafting autologous bone derived from the iliac crest resulted in density values of 406 to 420 HU and 510 to

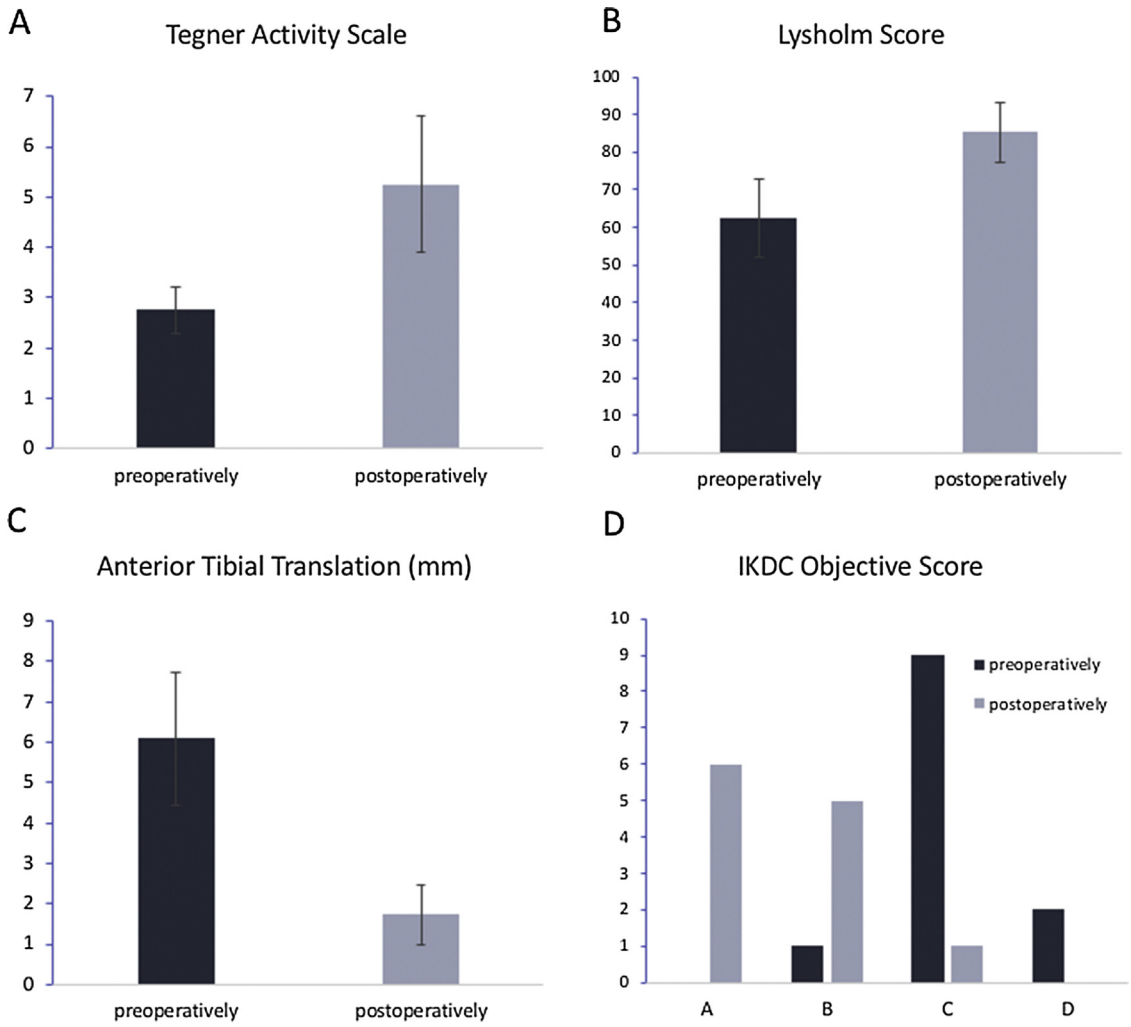

Fig. 4. Outcomes of revision ACL reconstructions secondary to reamer-irrigator-aspirator harvested bone grafting. The Tegner activity scale (A), the Lysholm score (B), the anterior tibial translations (C) and the IKDC objective score (D) were evaluated prior to the two-staged revision ACL reconstruction and at final follow-up. A significant postoperative improvement was revealed for all parameters ($p \leq 0.001$).

572 HU in other studies [39,41]. Despite the high density, histological examinations conducted by the van Recum group showed vital lamellar and cancellous bone in punch biopsy specimens taken from the filled voids during the second stage procedure. Taken together, the present findings demonstrate that the RIA bone grafting procedure ensures a sufficient and reliable tunnel filling with filling rates comparable to those reported for autologous bone grafts derived from the iliac crest or bone graft substitutes.

Successful filling of the preexisting tunnels should allow for anatomic tunnel positioning during the subsequently conducted revision ACL reconstruction. The relationship between anatomical reconstruction and translational/rotational stability as well as functional outcome has been repeatedly demonstrated in primary ACL reconstruction [43,44]. Nevertheless, data on the extend of anatomical tunnel positioning in two-staged revision ACL reconstruction is limited. At least, Thomas et al. assessed the tunnel placement before and after the two-staged revision ACL reconstruction [14]. Following the method of Aglietti et al. [45], the group determined the position of the anterior margin of the intraarticular aperture of the femoral and tibial tunnel on lateral radiographs as a percentage along the Bloomensaat's and the tibia plateau line, respectively. The preexisting tunnels had been placed too far anteriorly in the majority of patients. However, the bone grafting procedure allowed for satisfying placement of the revision tunnels in 48 of 49 patients. Unfortunately, Thomas et al. did not assess the tunnel placements on coronal planes. Furthermore, the comparability of tunnel positioning assessment across ACL studies is restricted by the large variety of methods and the lacking consensus of standardized protocols. For the purpose of the present case series, the placement of the preexisting tunnels was determined applying the grid method to 3D surface models of the lateral femur condyle and the tibial plateau [29,46]. Since CT scans are usually not applicable after the second stage procedure, the positioning of the revision ACL tunnels was analysed based on the two plane radiographs which were routinely conducted. The quadrant method was applied to the lateral view to determine the position of the femoral tunnel aperture [27]. The position of the tibial tunnel aperture was measured percentagewise form medial to lateral and form anterior to posterior analysing the coronal and lateral view, respectively [31–33,47]. Despite the limitations in direct comparability, the findings resemble the results revealed by Thomas et al. While the majority of preexisting femoral tunnels had been positioned too high and too shallow, all but one revision ACL tunnel could be positioned anatomically. At the tibia site, the RIA harvested bone grafting procedure allowed for anatomical tunnel positioning in all cases. The mean deviation of the aperture centre of the per-existing and the revision ACL tunnel from the

ideal insertion was improved significantly. Regarding the inclination angles of the femoral and tibial tunnel as well as of the tendon graft were shown to meet values observed in primary anteromedial portal ACL reconstructions [38,48–51]. Taken together, the present study reveals that the RIA harvested bone grafting procedure allows for anatomical positioning of the revision ACL tunnels.

Finally, the present study was conducted to investigate whether the introduced two-staged procedure does sufficiently restore the knee's stability and function. For this purpose, objective outcome parameters were determined at final clinical presentation. Additionally, subjective outcome was evaluated in a final survey after a mean interval of 37.1 months following the second stage procedure. Compared to the baseline, the anterior tibial translation and the IKDC objective sore improved significantly. At follow-up the patients showed a residual mean side-to-side difference of 1.7 mm (SD ± 0.8). This is comparable to results published by Thomas et al. who reported on a side-to-side difference of 1.36 mm (SD ± 1.1) after two-staged revision ACL reconstruction [14]. The altered distribution in the IKDC objective from baseline (B = 1, C = 9, D = 2) to final follow-up (A = 6, B = 5, C = 1) is also comparable to results revealed in other two-staged revision ACL reconstruction studies [40]. According to the improvements in objective outcome parameters, the mean values on the Tegner activity scale and the Lysholm score increased significantly when comparing baseline and follow-up. The Tegner activity scale revealed 5.3 points (SD ± 1.4) compared to 2.8 (SD ± 0.5) prior to the two-staged revision. The Lysholm score increased form 62.5 points (SD ± 10.5) to 85.4 (SD ± 7.9) at final follow-up. These findings match the results recently published in a meta-analysis on pooled one- and two-staged revision ACL reconstructions and clinical outcomes. The authors calculated a mean Tegner score of 5.0 and a mean Lysholm score of 87.5 after a mean follow up of 45.1 and 59.1 months, respectively [52]. Out of all 15 patients included in the present case series, one patient suffered a traumatic rerupture and was counted as failure. Taking into account that one patient was lost to follow-up and one patient refused to undergo the second stage procedure, it still meets the expectations of a failure rate of 8.9% published in the above mentioned meta-analysis [52]. To date, specific data on failure rates only for two-staged revision ACL reconstructions is lacking. In summary, the present study reveals reliable restoration of the knee's stability and satisfying functional outcomes of revision ACL reconstruction secondary to RIA harvested bone grafting. The limitations of the study are due to general case series designs. It will remain the assignment and focus of future comparative studies to validate the here introduced two-stage procedure in comparison to traditional two-stage procedures and primary ACL reconstruction. Further studies may also evaluate the potential for late tunnel dilation in the femur related to suspensory fixation and the 'windscreen wiper' effect.

Conclusion

Autologous RIA harvested bone grafting ensures sufficient bone stock consolidation which allows for anatomical tunnel placement during the subsequently conducted revision ACL reconstruction. The two-staged procedure reliably restores anterior tibial translation stability and provides satisfying subjective and objective outcomes. Thus, RIA harvested bone grafting is a promising alternative to iliac crest or allogenic bone grafting.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.injury.2018.12.020.

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