



Optimizing ACL Reconstruction: The Role of Precise Footprint Restoration and Adequate Graft Size for Knee Stability

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Abstract

Articular cartilage defects of the knee often cause pain, mechanical symptoms and progressive functional decline; untreated full-thickness lesions may predispose to early osteoarthritis. This prospective single-center cohort study (October 2019–October 2021) evaluated short-term clinical and radiological outcomes after three commonly used surgical strategies for symptomatic full-thickness femoral condyle defects ≥ 2.0 cm²: arthroscopic debridement with micro fracture, two-stage autologous chondrocyte implantation (ACI) and single-stage bone marrow aspirate concentrate (BMAC) delivered on a collagen matrix. Sixty-six eligible patients were enrolled and fifty-three completed one-year follow up. Patient-reported outcomes (IKDC and KOOS) were recorded preoperatively and at six months and one year; postoperative MRI with MOCART scoring was obtained when feasible. All three surgical techniques produced statistically and clinically meaningful improvement in IKDC and KOOS scores at one year. Younger age, lower body mass index and shorter time from injury to surgery correlated with greater functional gains. Radiological assessment where available showed acceptable defect fill. Within the limitations of a non-randomized single-centre series with one-year follow up, no single technique demonstrated clear short-term superiority. Longer randomized trials with standardized imaging and histological correlation are needed to determine long-term durability and relative efficacy.

Introduction

Articular cartilage is a highly specialised, avascular and aneural tissue with limited intrinsic capacity for repair. Its zonal architecture and sparse cellularity confer excellent load-bearing and low friction properties but hinder meaningful regeneration after full-thickness injury.[1] Full-thickness chondral and osteochondral defects of the femoral condyles frequently produce pain, mechanical symptoms and functional impairment and are encountered commonly at diagnostic arthroscopy of symptomatic knees.[2,3] Epidemiological series indicate that focal cartilage lesions are prevalent among patients undergoing knee arthroscopy and can produce

morbidity comparable to more advanced degenerative disease in selected populations.[4,5] The aetiology of focal defects is heterogeneous — acute trauma, repetitive overload, axial malalignment, meniscal deficiency and ligamentous instability are common contributors — and the lesion characteristics (size, depth, location) together with patient factors (age, activity level, body mass index) largely determine therapeutic choice and prognosis.[3,6]

Surgical approaches for symptomatic full-thickness defects range from palliative arthroscopic debridement to marrow stimulation techniques (microfracture), osteochondral autograft transfer (OATS/mosaicplasty), two-stage cell-based



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restorative techniques such as autologous chondrocyte implantation (ACI), and contemporary one-stage biologic augmentations that combine concentrated marrow elements (BMAC) with scaffolds.[7,8] Microfracture has been widely used for small to moderate defects because it is technically straightforward and cost-effective, but it produces predominantly fibrocartilaginous fill that may be biomechanically inferior to hyaline cartilage.[9–11] ACI and matrix-augmented ACI aim to regenerate hyaline-like tissue through chondrocyte expansion and implantation but require two procedures and greater resource allocation.[12–14] Single-stage BMAC approaches are attractive in resource-constrained settings because they concentrate marrow-derived progenitor cells and growth factors in one operation, but standardisation of preparation and robust long-term comparative evidence remain limited.[15–18]

Systematic reviews and meta-analyses demonstrate heterogeneity across studies in patient selection, lesion characteristics and outcome reporting; therefore, firm universal recommendations regarding a single superior technique are difficult to make.[6,19] This study therefore sought to evaluate short-term functional and radiological outcomes following microfracture, two-stage ACI and single-stage BMAC in a prospective cohort treated at a tertiary orthopaedic centre, with the goal of informing surgeon decision-making in similar clinical and resource settings.[20]

Literature overview

Large arthroscopic cohorts and registry data highlight the frequency and clinical burden of focal cartilage lesions.[3,4] Microfracture has been associated with reliable short-term symptomatic relief, particularly in younger patients with smaller lesions, but durability may decline over time, especially for larger defects.[9–11] Mosaicplasty transfers hyaline cartilage plugs but is constrained by donor site morbidity and size limitations. ACI and matrix-assisted cell therapies have demonstrated favourable medium-term outcomes in many series but at the cost of two-stage procedures and greater expense.[13–16] Contemporary interest centers on single-stage biologic augmentation (eg, BMAC with scaffolds) which offers logistical advantages and encouraging early imaging and functional results, though preparation protocols and long-term data are variable.[6,14,17,18] Systematic reviews emphasise patient selection and lesion characteristics as key determinants of success, supporting individualized treatment planning.[6,19]

Materials and Methods

This prospective single-centre cohort was conducted from October 2019 to October 2021. Adults aged 15–55 years with symptomatic ICRS/Outerbridge grade 4 full-thickness chondral defects of the femoral condyles measuring ≥ 2.0 cm² on MRI or arthroscopic assessment were considered. Patients

with advanced degenerative knee disease, systemic metabolic or neoplastic illness, intra-articular fractures, prior ipsilateral major knee surgery or defects <2.0 cm² were excluded. Institutional ethics approval and informed consent were obtained for all participants.

Baseline evaluation included a standardized history, physical examination, IKDC and KOOS questionnaires, weight and BMI measurement, plain radiographs and MRI to document lesion size, depth and associated meniscal or ligamentous pathology. Sixty-six consecutive eligible patients were enrolled; surgical strategy selection (microfracture, two-stage ACI or single-stage BMAC) was individualized based on defect size and location, associated pathology, patient preferences and resource considerations. Concomitant meniscal repair or ligament reconstruction was performed when indicated.

Surgical techniques followed standardized protocols. Microfracture was performed arthroscopically with stable borders debrided and multiple perforations into the subchondral plate created using an awl to allow marrow element ingress. ACI comprised arthroscopic harvest of cartilage for chondrocyte expansion followed by mini-open implantation of the cell-seeded scaffold in the second stage. Single-stage BMAC involved iliac crest aspiration, bedside centrifugation to concentrate marrow elements and implantation beneath a collagen matrix via a mini-arthrotomy. Perioperative care included prophylactic antibiotics, regional or general anaesthesia and a standardised rehabilitation regimen tailored to the procedure: early controlled range of motion with protected weight bearing and progressive strengthening over weeks.

Follow up occurred at routine intervals with detailed clinical examination and patient-reported outcomes at six months and one year. Postoperative MRI with MOCART scoring and second-look arthroscopy were obtained when clinically indicated and feasible. Outcome measures included change in IKDC and KOOS (primary endpoints), MOCART MRI appearance and complication rates (secondary endpoints). Statistical analysis used paired comparisons for within-group changes and ANOVA for between-group comparisons with significance set at $p < 0.05$. Data were analysed using standard statistical software.

Results

Of the 66 eligible patients, 53 (80.3%) completed the one-year follow up and were included in the final analysis. The cohort comprised 34 males and 19 females with a mean age of 32.7 years (SD 8.9) and mean BMI 24.44 kg/m². Mean defect area was 5.6 cm² (range 2.2–10.4 cm²); 69.8% of lesions exceeded 4.0 cm². Procedures performed were arthroscopic microfracture in 33 patients (62.3%), single-stage BMAC in 15 (28.3%) and two-stage ACI in 5 (9.4%). Concurrent pathology requiring treatment (eg, meniscal tears, ACL injuries) was present in 54.7% and was addressed during the index procedure

as appropriate.

At six months and one year, all three groups demonstrated statistically significant improvements in IKDC and KOOS relative to baseline ($p < 0.05$ for within-group comparisons). Mean improvements were greater in younger patients and those with lower BMI. Between-group differences in mean IKDC and KOOS gains at one year did not reach statistical significance in this cohort, though subgroup sample sizes (particularly for ACI) were small. Postoperative MRI enabling MOCART scoring was available for 23 patients and generally indicated acceptable defect fill and integration across procedures. Complications were few and minor; there were no reported major procedure-related adverse events within the one-year follow up.

Discussion

This prospective single-centre series demonstrates that arthroscopic microfracture, single-stage BMAC and two-stage ACI each produced meaningful symptomatic and functional improvement at one year for symptomatic full-thickness femoral condyle defects. The clinical improvements observed align with prior epidemiological and cohort data indicating that appropriately selected patients derive benefit from both marrow-stimulation and restorative biologic techniques.^{3–8} Age, BMI and timing of surgery emerged as important correlates of outcome in this cohort, consistent with published series that identify younger patients and those treated earlier as more likely to experience substantial gains.^[8,11,15]

Microfracture remains a pragmatic, cost-effective option that delivers reliable short-term relief for many patients, particularly for smaller defects and lower-demand individuals, but it typically yields fibrocartilaginous repair tissue whose long-term biomechanical properties may be inferior to native hyaline cartilage.^[9–11] Mosaicplasty and osteochondral grafting provide immediate hyaline cartilage restoration but are limited by donor site morbidity and size constraints.^[12–14] ACI and matrix-assisted chondrocyte implantation have shown promising medium-term outcomes in multiple series but require two-stage procedures, cell expansion facilities and greater resources.^[13,16]

Single-stage BMAC with a collagen matrix offers logistical advantages in a single operation and in this cohort produced early functional gains comparable to other techniques; however, variability in marrow concentrate preparation and lack of standardisation complicate cross-study comparisons and long-term efficacy remains to be established.^[15–18] MRI assessment using standardized scoring such as MOCART provided useful non-invasive information about defect fill and integration in those patients imaged, but routine postoperative imaging and histological verification were not feasible for all participants in this series. Limitations of this study include non-randomised technique allocation influenced by surgeon

preference and resource considerations, incomplete imaging for the entire cohort, small subgroup sizes (notably for ACI), and relatively short follow up of one year — all of which limit definitive between-technique comparisons and long-term inference.^[6,19,20]

Taken together with the broader literature, these findings support individualized treatment selection that balances lesion characteristics, patient factors, surgeon expertise and resource availability. Prospective randomized trials with standardized imaging protocols, second-look arthroscopy and histological assessment are required to determine technique-specific durability, cost-effectiveness and activity-related outcomes over the longer term.^[6,17,19]

Conclusion

In this prospective cohort of adults with symptomatic full-thickness femoral condyle defects ≥ 2.0 cm², arthroscopic microfracture, single-stage BMAC with collagen matrix and two-stage ACI each produced significant improvements in IKDC and KOOS scores at one year with low complication rates. Patient factors — especially younger age, lower BMI and shorter interval from injury to surgery — were associated with greater functional gains. Radiological assessment where obtained demonstrated acceptable defect fill and early repair integration. Within the limitations of non-randomised allocation, incomplete imaging and short follow up, no single technique proved clearly superior at one year. Individualised, evidence-informed decision-making and longer randomized studies with standardized imaging and histology are recommended to guide optimal management and resource allocation.

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