Bone Marrow Aspirate Concentrate May Decrease Reoperation in Osteochondral Allograft Transplantation: A Prospective, Randomized, Double-Blind Investigation

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Purpose: To perform a prospective, double-blind, randomized controlled trial to assess differences in integration and patient-reported outcomes metrics (PROMs) of osteochondral allograft transplantation with and without bone marrow aspirate concentrate (BMAC) augmentation. **Methods:** Patients (n = 36) undergoing osteochondral allograft transplantation of the knee were consented and enrolled in this prospective study. They were randomized to either iliac crest BMAC or sham incision groups and blinded to their allocation. Computerized tomography (CT) scans of the knee were obtained at 6 months postoperatively after the index transplantation and graded by the semiquantitative assessment CT osteochondral allograft system. PROMs, including the International Knee Documentation Committee and Knee injury and Osteoarthritis Outcome Score—Joint Replacement, were obtained at 6 months, 1 year, and 2 years postoperatively. **Results:** On 6-month postoperative CT scans, patients receiving BMAC-treated grafts were more likely to have small cystic changes ($P = .01$), with an associated trend toward reduction in large cyst formation ($P = .06$), but equal osseous integration, graft signal density, and presence of discernible clefts and intra-articular fragments. The BMAC group was less likely to undergo subsequent surgery for graft debridement or revision (5.3% vs 35.3%; $P = .02$). There were no significant differences in PROMs between the 2 groups preoperatively or postoperatively at 6 months, 1 year, or 2 years. Patients receiving BMAC trended toward a higher rate of achievement of Knee Documentation Committee and Knee injury and Osteoarthritis Outcome Score—Joint Replacement minimal clinically important difference (88% vs 55%; $P = .076$). **Conclusions:** Patients receiving BMAC-treated grafts were more likely to have small cystic changes and were less likely to undergo subsequent surgery for persistent or new symptoms after the index procedure. No difference in postoperative PROMs was shown at the 6-month, 1-year, and 2-year follow-ups between the 2 groups. **Level of Evidence:** Level I, prospective, randomized controlled trial.

Full-thickness articular cartilage defects of the knee are a common cause of pain and disability in the young, active patient population.[1,2] While such lesions present a significant treatment challenge, advances in surgical techniques have equipped surgeons with multiple options to more reliably restore a functional articular surface.[3-6] Among these techniques, osteochondral allograft transplantation (OCA) is becoming increasingly preferred as a primary or salvage treatment option due to reduced operative time, the ability to treat larger defects while eliminating donor site morbidity, and early full load bearing upon osseointegration.[7-13] Many studies have shown positive outcomes following OCA in the short and long term, including improvement in pain and functional status.[14-18] However, these positive outcomes largely hinge on successful graft osseointegration,[19,20] which consists of bone-to-bone healing as well as cellular repopulation of the acellular and avascular allograft bone.[21-24] Consequently, there is increasing interest in supplemental

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treatments that may accelerate the cellular repopulation and neovascularization process.

Recently, the therapeutic value of bone marrow aspirate concentrate (BMAC), an autologous mixture of concentrated marrow elements, including multipotent stem cells and growth factors,[25] has been investigated as an adjunct to cartilage restoration procedures, showing inconclusive results.[26-31] In the context of OCA, early results have suggested that BMAC may improve cellular repopulation and viability within the osseous portion of an implanted graft.[32] However, few clinical studies to date have investigated the impact of BMAC on clinical patient outcomes following OCA.[33-35] None of these studies included patient-reported outcome metrics (PROMs), and all were Level III cohort studies.

Therefore, the purpose of this study was to perform a prospective, double-blind, randomized controlled trial to assess differences in integration and PROMs of osteochondral allograft transplantation with and without BMAC augmentation. We hypothesized that graft pretreatment with autologous BMAC would enhance graft osseointegration and lead to earlier improvement in patient-reported outcome scores.

Methods

After institutional review board approval at Rush University Medical Center, patients between the ages of 18 and 50 years undergoing osteochondral allograft transplantation of the knee with 1 of 3 senior authors (A.B.Y., B.F., B.J.C.) were consented and enrolled. Exclusion criteria for enrollment included a history of inflammatory arthropathy and osteoarthritis of the knee, as determined by a Kellgren-Lawrence grade 3 or higher on preoperative radiographs. Defects of all sizes were included in the study. Before surgery, patients were randomized into either the BMAC or sham incision groups, utilizing random sequence generation for enrollment. Randomization occurred before the enrollment of any patients, and opaque envelopes were used to conceal the cohort assignments for the study. A total of 37 patients were randomized and included to account for the possibility of a patient lost to follow-up. All patients were blinded to their treatment group (Fig 1).

BMAC Harvest and Technique

Before initiation of the procedure, a sterile bone marrow harvest was performed for patients randomized to the true BMAC group. A bone marrow aspiration was performed under sterile conditions from the iliac crest using a 0.5-cm percutaneous incision until at least 60 mL was obtained.

The bone marrow aspirate was then processed utilizing the Angel Bone Marrow Processing System (Arthrex) according to the manufacturer's instructions. The expected output of the Arthrex Angel processing system has been previously described.[36] This resulted in approximately 3 to 4 mL of BMAC. Before osteochondral allograft implantation, the plug was irrigated

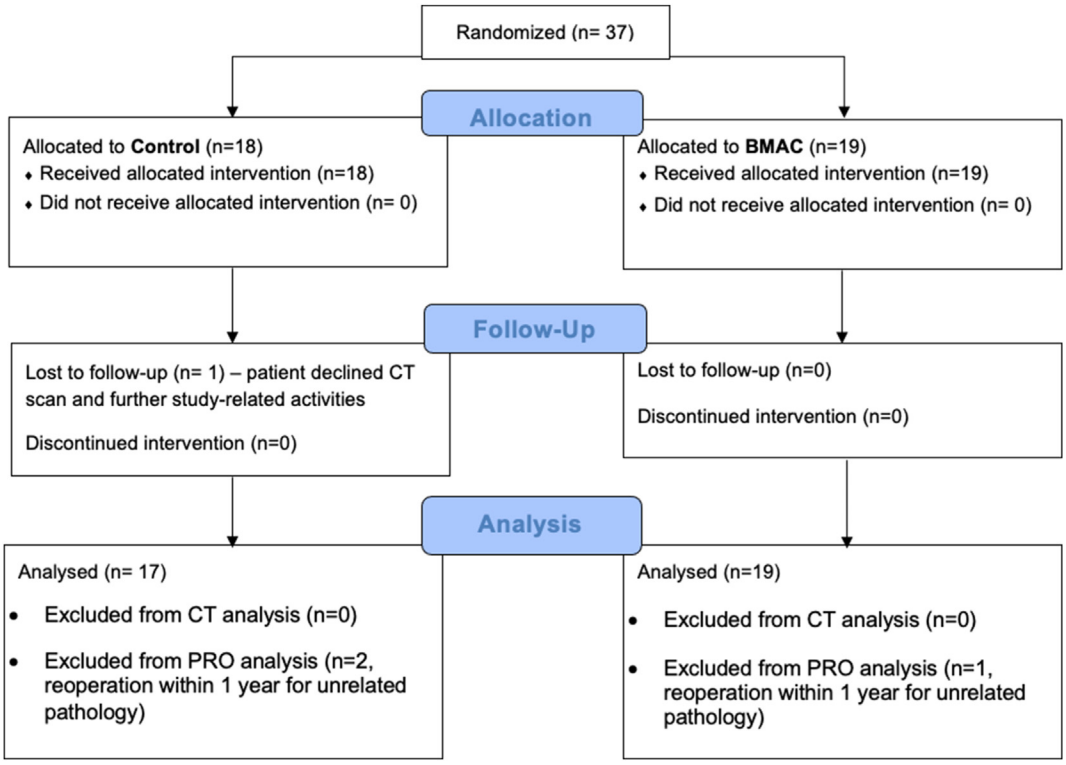

Fig 1. Consolidated Standards of Reporting Trials flow diagram for inclusion.

copiously to remove marrow elements, with either pulse lavage or pressurized carbon dioxide systems, and subsequently soaked in BMAC for a minimum of 2 minutes (Video 1). The remaining procedure was conducted as previously described in the literature (Fig 2).

Patients randomized to the sham incision group received a 0.5-cm incision over the iliac crest to simulate a bone marrow harvest. The sterile preparation, size of the incision, location of the incision, and closure were identical between BMAC and sham groups.

Surgical Technique

The technique for osteochondral allograft preferred by the senior authors (A.B.Y., B.F., B.J.C.) has previously been described by Stone et al.[37] and Allahabadi et al.[38] In summary, a diagnostic arthroscopy is first performed to evaluate concomitant pathology. Subsequently, a medial or lateral parapatellar arthrotomy is performed to expose the defect. After centering a sizing cylinder over the defect, a reamer is drilled over a guide pin to a depth of approximately 6 to 8 mm. After removal of the recipient osteochondral core, the defect depth is measured at 12-, 3-, 6-, and 9-o'clock positions. An appropriately sized allograft plug is then fashioned, with special attention paid to proper surface topography matching. Donor residual marrow elements are removed from the allograft with either pulse lavage or pressurized carbon dioxide. If the patient was randomized to receive BMAC, the graft is then soaked in the BMAC after removal of the donor residual marrow elements. The plug is then press-fit into the recipient site.

Primary Outcome

All patients underwent postoperative computed tomography (CT) scanning of the knee at 6 months postoperatively. Three board-eligible orthopaedic surgeons (B.M.B., N.A.T., M.H.) blinded to treatment allocation independently assessed and graded each CT scan according to the assessment CT osteochondral allograft (ACTOCA) system proposed by Gelber et al.[39] The components of grading included (1) graft signal density relative to host bone, (2) osseous integration at the host-graft junction, (3) surface percentage with a discernible cleft at the host-graft junction, (4) cystic changes of graft and/or host-graft junction, and (5) presence of intra-articular fragments. The final grades per category for each graft were determined by majority consensus measurements between the 3 graders.

Secondary Outcomes

Patients were asked to complete the following PROMs preoperatively and 6 months, 1 year, and 2 years postoperatively: International Knee Documentation Committee (IKDC) and Knee injury and Osteoarthritis Outcome Score—Joint Replacement (KOOS JR) scores.

Subsequent surgeries on the index knee were assessed by contacting patients, clinical visits, and internal review at a minimum of 1 year postoperatively. Failure was defined as symptomatic graft hypertrophy, fissuring, cystic change, or collapse of the osteochondral allograft, prompting debridement or revision.

Statistical Analysis

All statistical analysis was performed using STATA v16.1 (StataCorp) and RStudio (software version 4.1.0; R Foundation for Statistical Computing). All descriptive statistics are reported as mean ± standard deviation or percentages where appropriate. Interobserver reliability was established for CT grading for each subscore, and agreement statistics with associated κ were calculated. Student t tests and χ^2 analyses were performed for comparison of continuous demographic and categorical outcomes, respectively. Normality of patient-reported

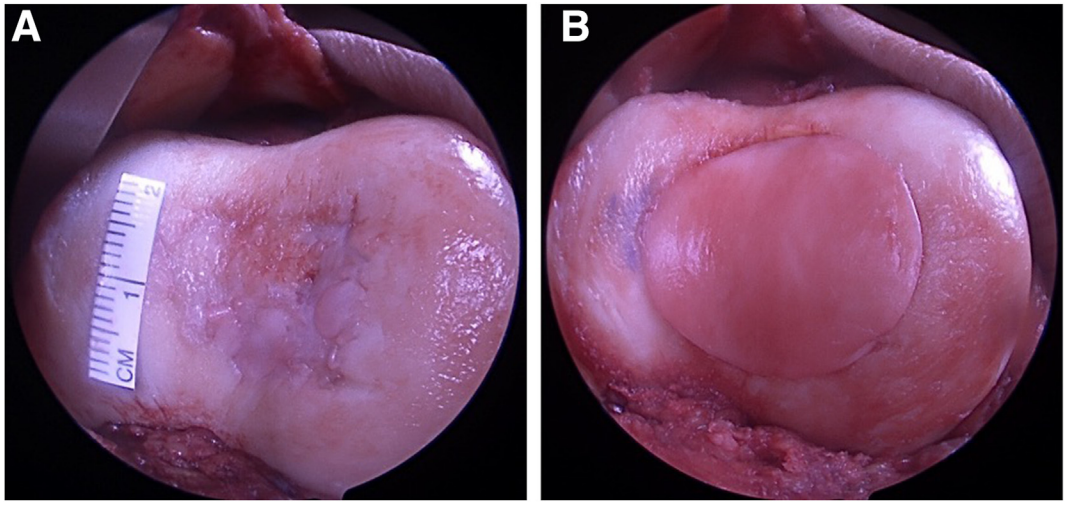

Fig 2. Osteochondral allograft transplantation for a large central trochlear defect.

outcome data, as determined by the Shapiro-Wilk test, showed some data to be nonparametric. Therefore, a nonparametric Wilcoxon rank-sum test was performed to compare PROMs between the experimental and control groups. Testing was 2-sided, and significance was set to $P < .05$. Target sample size was determined a priori by both related literature and power analysis. Oladeji et al.[34] explored radiographic differences in osteochondral allograft healing in 46 patients, and Brown et al.[40] analyzed graft incorporation by CT scanning in 34 patients. This sample of 36 patients was selected to achieve 80% power, with an α of 0.05 and 2 degrees of freedom, to detect differences in healing metrics, such as graft osseous integration signal density, of a large effect size ($w = 0.52$).

Results

Study Sample Demographics

Thirty-seven patients consented to this study between April 2018 and December 2020. One patient in the sham incision (control) group declined the CT scan at 6 months and withdrew from the study. This patient was thus excluded from analysis, leaving a final cohort of 36 patients (17 women, 19 men). Demographic comparison between the 2 groups is presented in Table 1. All patients had at least 1 prior surgery on the ipsilateral knee, including 6 anterior cruciate ligament (ACL) reconstructions, 1 medial patellofemoral ligament reconstruction with a tibial tubercle osteotomy, 1 matrix-induced autologous chondrocyte implantation, and 1 open reduction and internal fixation of a lateral trochlear osteochondral defect. Two patients in the control group had prior BMAC injections in the ipsilateral knee, but these injections were unlikely to be of significance due to the length of time between these injections and surgery, as well as the lack of BMAC being soaked into the osseous surface of the OCA plug.

Osteochondral Allograft Transplantation

In patients randomized to the BMAC group with multiple defects, all implanted grafts were pretreated with BMAC. Thirty patients received osteochondral allograft plugs to 1 defect location, including 16 medial femoral condyles (MFCs), 6 lateral femoral condyles (LFCs), 2 trochlea, and 6 patella. Most of these (n = 28) were single circular plugs; 1 patient received an oblong plug for an MFC defect, and 1 patient received 2 osteochondral plugs in a "snowman" configuration for an MFC defect. Four patients received allografts for 2 defect locations: 2 MFCs and trochlea, 1 MFC and LFC, and 1 LFC and patella. Two patients received allografts to 3 locations: (1) patella, trochlea, and LFC and (2) trochlea, MFC, and LFC.

Table 1. Study Demographics

Characteristic	Control (n = 17)	BMAC (n = 19)	*P* Value
Age, y	29.9 ± 8.8	34.3 ± 9.5	.16
Sex (M:F)	13:4	6:13	**.01**
Body mass index	27.7 ± 4.2	27.7 ± 5.2	.97
Concomitant surgery	MMAT, ACLR	TTO (3)	.10
	MMAT, rACLR	MM root repair	
	TTO	MPFLR	
	MM root repair	MPFLR + TTO	
	MPFLR + TTO	LMAT	
	Medial Mx	DFO rACLR + HTO	
		MMAT	
Prior history	BMAC injection, Mfx augmentation	ACL, Mfx, ACLR (4), PCLR	—
	BMAC injection, meniscectomy		
	ACL, Mfx, MACI, MPFL + TTO, ACLR		
OCA grafts	7 MFC	7 MFC	.46*
	3 LFC	3 LFC	
	1 patella	5 Patella	
	2 trochlea	1 MFC + trochlea	
	1 MFC (snowman)	1 patella + LFC	
	1 MFC (Biouni)	1 trochlea + MFC + LFC	
	1 MFC + trochlea	1 MFC + LFC	
	1 patella + trochlea + LFC		

NOTE. Difference between groups for prior history was not calculated as all patients had prior surgery. Age and body mass index are expressed as mean ± standard deviation. Bold values represent statistically significant difference ($p \leq 0.05$).

ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; BMAC, bone marrow aspirate concentrate; DFO, distal femoral osteotomy; HTO, high tibial osteotomy; LFC, lateral femoral condyle; MACI, matrix-associated autochondrocyte implantation; MFC, medial femoral condyle; Mfx, microfracture; MM, medial meniscus; MMAT, medial meniscal allograft transplantation; MPFL, medial patellofemoral ligament; MPFLR, medial patellofemoral ligament reconstruction; Mx, menisectomy; PCLR, posterior cruciate ligament reconstruction; rACLR, revision anterior cruciate ligament reconstruction; TTO, tibial tubercle osteotomy.

*Comparison of patients with single versus multiple site grafts.

Concomitant procedures were performed in 18 patients (50%), including 7 tibial tubercle osteotomies, 2 medial meniscal root repairs, 2 medial patellofemoral ligament reconstructions, 2 realignment osteotomies (1 high tibial osteotomy, 1 distal femoral osteotomy), and 3 ACL reconstructions (including 2 revision cases). The rate of concomitant procedures did not significantly differ between BMAC and control groups ($P = .1$).

Postoperative CT Imaging Characteristics

All patients underwent postoperative CT imaging at a mean of 6.38 ± 1.17 months after transplantation. Three fellowship-trained orthopaedic surgeons graded each CT scan according to the ACTOCA system. Overall, 44 grafts were evaluated in 36 patients. The interobserver agreement was moderate to substantial (κ range, 0.43-0.70; $P < .001$) for all measures (Appendix Table 1, available at www.arthroscopyjournal.org). The final classification by study group is presented in Table 2.

There were no significant differences between the BMAC and control groups in graft signal density ($P = .47$), osseous integration ($P = .49$), surface percentage with discernible cleft ($P = .47$), or intra-articular fragments ($P = .81$). While there was no significant difference in overall prevalence of cystic changes between the 2 groups ($P = .28$), there was a significant difference in size distribution of such changes ($P = .03$, Fig. 3). Post hoc subgroup analysis showed a significant increase in small cyst formation in the BMAC group ($P = .01$) associated with a trend toward a decrease in large cyst formation ($P = .06$, Fig. 4).

Table 2. Categorization of Osteochondral Allografts by Imaging Analysis

Characteristic	Control	BMAC	*P* Value
Graft signal density			
Equivalent	7	11	.47
Superior	13	13	
Inferior	0	0	
Osseous integration			
Crossing trabeculae	10	16	.49
Cleft <3 mm	8	7	
Cleft >3 mm	2	1	
Surface percentage with discernible cleft			
<30%	13	18	.47
>30%	7	6	
Intra-articular fragments			
Absent	17	21	.81
Present	3	3	
Cystic changes			
Absent	9	7	**.03**
Present <3 mm	5	15	
Present >3 mm	6	2	

NOTE. Numbers in this table represent the number of osteochondral allografts implanted.

BMAC, bone marrow aspirate concentrate.

Bold numbers represent statistically significant difference ($p \leq 0.05$).

Subsequent Surgeries and Survival Analysis

Seven patients (1 BMAC, 6 control) required graft debridement for new-onset pain or mechanical symptoms after the index procedure at a mean of 1.6 ± 1.0 years postoperatively (Table 2), with a significantly greater occurrence of failure in the control group (35.3%) compared to the BMAC group (5.3%) ($P = .023$). All occurrences of failure were with the graft placed in the MFC. The 1 patient in the BMAC group who did not respond to treatment received a concomitant meniscal allograft transplantation, and 1 control patient with an unsuccessful treatment received a meniscal root repair, with the rest receiving no concomitant procedures. All patients who did not respond to treatment had less than 5° of varus long-leg axis malalignment (range, 0.4°-4.4°). Within the control group, 1 patient had significant subchondral cyst formation with mild collapse of the graft, prompting partial removal of the graft, and 1 patient required a revision osteochondral allograft procedure. The remaining patients had mild fibrillation, fraying, or peripheral cartilage loss, which was debrided to stable edges (Table 3). Mean clinical follow-up time was equivalent between groups (1.5 ± 0.70 vs 1.5 ± 0.68 years; $P = .80$). Distribution of time to failure did not significantly differ between the 2 groups ($P = .10$; Fig 5).

Two patients required subsequent surgeries unrelated to the osteochondral allograft, including 1 revision ACL reconstruction with meniscal repair and 1 tibial tubercle fracture revision reduction and fixation, at a mean of 5.44 ± 0.79 months after the index transplant procedure. These were not included in the calculation of failure rates.

Patient-Reported Outcomes

Two patients underwent additional procedures within the first postoperative year for pathology unrelated to the graft and were therefore excluded from PROM analysis. One patient did not complete preoperative PROMs. Minimal clinically important difference (MCID) at the 1-year follow-up was calculated to be 10.01 for IKDC and 7.96 for KOOS JR using half the standard deviation of the difference between 1-year PROMs and preoperative PROMs. For IKDC, 81% and 75% ($P = .99$) of patients in the BMAC and control groups, respectively, reached MCID. For KOOS JR, the difference in achievement of MCID trended toward significance, with 88% and 55% ($P = .076$) in the BMAC and control groups reaching MCID. No statistically significant differences in IKDC or KOOS Jr. scores were observed between the BMAC and control groups at any time point (Table 4).

Discussion

This prospective, double-blind, randomized controlled trial was conducted to investigate the effect of BMAC on integration and outcomes after osteochondral

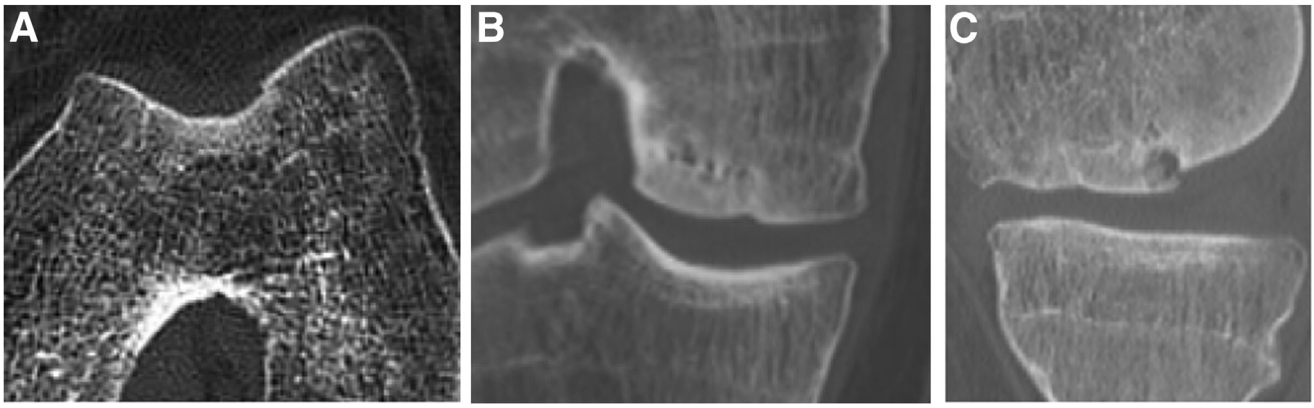

Fig 3. Sample patient images showing the range of cystic changes, from none (A) to small, defined as <3 mm (B), and large, defined as >3 mm (C).

allograft transplantation, showing reduced reoperation with the incorporation of BMAC in OCA transplantation. At 6 months postoperatively, patients receiving BMAC were more likely to have small cystic changes, associated with a trend toward concurrent reduction of large cyst formation ($P = .06$). There were no significant differences in osseous integration, graft signal density, cleft formation, or intra-articular fragments between the BMAC and control groups. However, patients receiving BMAC were less likely to undergo a subsequent surgery for debridement or revision of the graft (5.3% vs 35.3%; $P = .02$). Patients receiving BMAC also trended toward a high rate of achieving 1-year KOOS JR MCID (88% vs 55%; $P = .076$).

The findings of this current study most closely support those of a separate retrospective review by Wang et al.[33] They evaluated differences in graft integration on magnetic resonance imaging (MRI) between cohorts of patients who underwent OCA with and without BMAC augmentation. The authors concluded that BMAC provided no benefits to the OCA procedure with regard to osseointegration or other features evaluated according to the Osteochondral Allograft MRI Scoring System. They noted that MRI was more capable of evaluating the entire graft-host interface than orthogonal radiographs. In the early postoperative phase (6 months), 71% to 81% of their patients had discernible clefts, and 25% to 41% had cystic changes. The findings from our study showed approximately 40% of grafts with discernible clefts and approximately 60% with cystic changes. The higher rate of cyst detection may in part be due to the higher spatial resolution of the CT scan. Further investigation is required to evaluate the

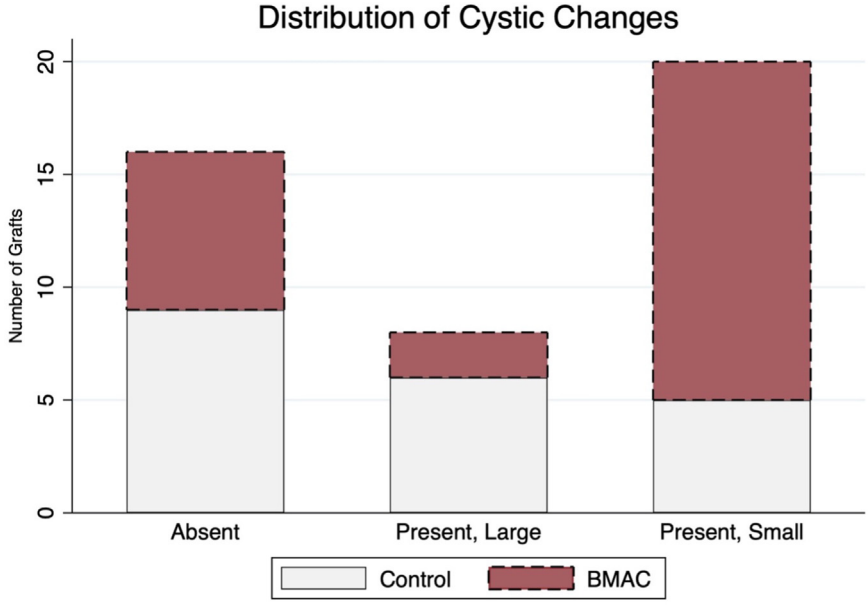

Fig 4. Distribution of cystic changes between bone marrow aspirate concentrate and control groups.

Table 3. Descriptive Analysis of Surgical Failures

Demographics	Transplant Locations (BMAC ±)	Time to Failure, y	CT Findings (Cysts)	Clinical Course	Surgical Findings
20, female	Patella, trochlea, LFC (−)	0.9	2/3 grafts with small cystic changes	Continued clinical symptoms	Fibrillation surrounding patellar graft, fibrillation of LFC graft. No delamination or loosening, debridement
19, male	MFC (−)	1.0	Small cystic changes	Initial improvement, new-onset pain and swelling	Intact graft with fraying in the periphery, debridement
40, male	MFC (−)	1.0	Large cystic changes	Continued clinical symptoms	Loose edge of graft from collapse associated subchondral cyst, fragment excision
41, male	MFC, trochlea (−)	1.7	Small cystic changes	Daily symptoms, discomfort with weightbearing.	Intact grafts; new trochlear defect; peripheral thinning of cartilage surrounding MFC graft
39, male	MFC (−)	2.1	Large cystic changes	Continued symptoms	Fibrillation, fraying around the edges, revision graft with HTO
34, male	MFC (−)	3.6	Large cystic changes	Improvement 3+ years, sudden-onset pain after activity	Degenerative circumference with peripheral degenerative disease
19, female	MFC (+)	1.1	Small cystic changes	Initial improvement, new-onset pain, particularly over incision	Degeneration in 1 of 2 plugs

NOTE. Gray indicates BMAC group, and white indicates control group.

BMAC, bone marrow aspirate concentrate; CT, computed tomography; HTO, high tibial osteotomy; LFC, lateral femoral condyle; MFC, medial femoral condyle.

differences in imaging interpretation and detection of pathologic changes across imaging modalities. Other than the cystic changes, the other imaging parameters were largely equal in distribution compared to this study.

The formation of subchondral cysts in the early postoperative phase is a concerning aberration in the healing process, as the integration of an OCA graft depends on adequate remodeling of the subchondral bone.[41] A translational study by von Rechenberg et al.[42]

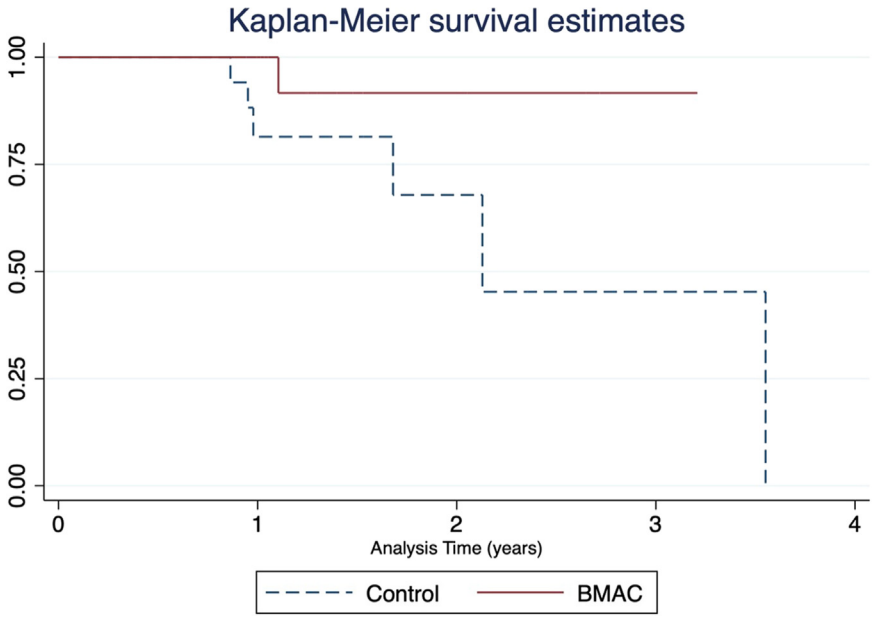

Fig 5. Kaplan-Meier curve for time to surgical failure between bone marrow aspirate concentrate and control groups ($P = .10$ by log rank analysis).

identified that grafts with the fastest rates of bone resorption and remodeling were more likely to develop cyst-like lesions and that, despite complete remodeling by 12 months, grafts that maintained structural integrity still had diminished chondrocyte viability. Furthermore, cyst formation in the setting of cartilage restoration has been associated with poorer midterm clinical outcomes,[43,44] suggesting that the early postoperative healing phase may strongly dictate the outcome of the graft, even in the setting of maintained structural integrity.

The trend of a downward "shift" in large cyst development would be concordant with the expected function of BMAC in this application. Specifically, the concentrated presence of mesenchymal stem cells, transforming growth factor B, bone morphogenic protein, and IL-1Ra has been suggested to play a role in improving graft integration and decreasing inflammation.[25,45,46] These findings oppose those findings of Shimozono et al.,[43] who showed a significant decrease in any cyst formation in patients undergoing autologous osteochondral transplantation of the talus augmented with BMAC compared to a control group, but the trend toward fewer large cyst formation suggests the current study may show similar protection from cyst proliferation as Shimozono et al.[43] Similarly, the current study identified no significant differences in functional or subjective outcomes. Notably, other factors that have been associated with cyst formation, such as bony thickness (<5 mm) of the osteochondral plug, were not accounted for in the present study.[47] Furthermore, the relevance of cyst size (<3 mm vs >3 mm) on graft incorporation and failure is yet to be elucidated.

The application of BMAC for osteochondral allograft transplantation was first explored by Oladeji et al.[34] in a retrospective study, reporting the radiographic outcomes of 15 patients who underwent OCA without BMAC and 22 patients implanted with OCA grafts treated with BMAC. This study showed higher graft integration scores up to 6 months postoperatively and less graft sclerosis in the BMAC group up to 3 months postoperatively.[34] Only 1 bone healing complication requiring revision at 7 months postoperatively was identified in the control group. Based on these findings, the authors conclude that expedited healing in the early postoperative setting may help mitigate failure. Although the current study was unable to assess the rate of healing longitudinally, due to the one-time CT scan, we identified no differences in healing other than the presence of cystic changes between the BMAC and control groups. However, the ACTOCA grading system is a highly granular system, requiring categorization of integration into 2 to 3 categories, while the study by Oladeji et al.[34] utilized a continuous measure (percentage of integration), which would likely be more sensitive to detecting differences than a category-based system.

Table 4. Patient-Reported Outcomes

Characteristic	Control	BMAC	*P* Value
Preoperative (n = 33, 15 control; 18 BMAC)			
IKDC	37.5 (28.5)	38.2 (13.2)	.87
KOOS JR	54.8 (15.1)	56.0 (11.4)	.82
6 months (n = 32, 15 control; 17 BMAC)			
IKDC	50.0 (31.3)	49.0 (19.3)	.97
KOOS JR	70.0 (15.7)	68.3 (14.8)	.84
1 year (n = 29, 13 control; 16 BMAC)			
IKDC	58.0 (20.4)	58.5 (26.7)	.78
KOOS JR	70.7 (12.2)	73.4 (18.6)	.49
2 years (n = 24, 10 control; 14 BMAC)			
IKDC	63.4 (18.1)	64.9 (24.1)	.71
KOOS JR	74.9 (18.6)	73.6 (13.6)	.95

NOTE. Values are reported as median (interquartile range).

BMAC, bone marrow aspirate concentrate; IKDC, International Knee Documentation Committee; KOOS JR, Knee injury and Osteoarthritis Outcome Score—Joint Replacement.

Oladeji et al.[34] had proposed that these differences in healing may contribute to increased survival of the graft. In the current study, only 1 of 6 patients requiring a subsequent debridement or revision was in the BMAC group. Due to continued medial-sided knee pain, particularly in the compartment of the initial transplant, the patient underwent a second-look arthroscopy. Significant degeneration was noted in 1 of 2 plugs of the snowman configuration. Five cases of reoperation were noted in the control group, with 2 of 5 patients requiring major revision or graft removal procedures for significant collapse or complex pathology with persistent symptoms. Our findings of failure rates and survival time were significant ($P = .023$), showing improved survival with BMAC augmentation, albeit with a small sample size, which should prompt further investigation into the hypothesis proposed by Oladeji et al.[34]

Limitations

There remain several important limitations. First, concomitant surgeries (e.g., meniscal allograft transplantation, osteotomies) were not considered exclusion criteria for this investigation. While these additional surgeries may not have interfered with imaging of allograft healing, true differences in patient-reported outcomes may be diluted by heterogeneity. Furthermore, the small sample size limits the ability to conduct subanalyses based on these concomitant procedures. Another similar limitation was the inclusion of several transplant locations and the number of grafts, which also contributes to a more heterogeneous cohort. Additionally, confounding variables that may influence graft survival, such as mechanical axis malalignment,

could not be controlled for. The current investigation was not powered to detect changes in PROM scores, so the possibility of type II error regarding the PROM analysis is large. Likewise, the current study was not powered to disaggregate the data by sex, and therefore this analysis was not included. Separately, although the study strived for a standardized CT scanning window, a small sample of patients (n = 5) required a CT date outside of the established window (5-7 months). This may increase the heterogeneity of imaging data. Moreover, CT scanning is unable to give us information on the viability of the cartilage layer of the osteochondral allograft, which is essential for graft survival. Lastly, the contents of BMAC were not formally characterized, and therefore the inherent variability between patients could not be quantified or analyzed.

Conclusions

Patients receiving BMAC-treated grafts were more likely to have small cystic changes and were less likely to undergo subsequent surgery for persistent or new symptoms after the index procedure. No difference in postoperative PROMs was shown at the 6-month, 1-year, and 2-year follow-ups between the 2 groups.

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Disclosures

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References

1. Flanigan DC, Harris JD, Trinh TQ, Siston RA, Brophy RH. Prevalence of chondral defects in athletes' knees: A systematic review. *Med Sci Sports Exerc* 2010;42:1795-1801.
2. Heir S, Nerhus TK, Røtterud JH, et al. Focal cartilage defects in the knee impair quality of life as much as severe osteoarthritis: A comparison of knee injury and osteoarthritis outcome score in 4 patient categories scheduled for knee surgery. *Am J Sports Med* 2010;38:231-237.
3. Brophy RH, Wojahn RD, Lamplot JD. Cartilage restoration techniques for the patellofemoral joint. *J Am Acad Orthop Surg* 2017;25:321. doi:10.5435/JAAOS-D-15-00447
4. Wang AS, Nagelli CV, Lamba A, Saris DBF, Krych AJ, Hevesi M. Minimum 10-year outcomes of matrix-induced autologous chondrocyte implantation in the knee: A systematic review. *Am J Sports Med* 2024;52:2407-2414.
5. Kunze KN, Persaud S, Briano J, et al. Outcomes of revision cartilage restoration surgery for failed primary treatment of chondral or osteochondral defects of the knee: A systematic review. *Am J Sports Med* 2025;53:1515-1523.
6. Gudeman AS, Hinckel BB, Oladeji L, et al. Evaluation of commercially available knee cartilage restoration techniques stratified by FDA approval pathway. *Am J Sports Med* 2022;50:3698-3704.
7. Pearsall AW, Tucker JA, Hester RB, Heitman RJ. Chondrocyte viability in refrigerated osteochondral allografts used for transplantation within the knee. *Am J Sports Med* 2004;32:125-131.
8. Krych AJ, Robertson CM, Williams RJ, Cartilage Study Group. Return to athletic activity after osteochondral allograft transplantation in the knee. *Am J Sports Med* 2012;40:1053-1059.
9. Chahla J, Sweet MC, Okoroha KR, et al. Osteochondral allograft transplantation in the patellofemoral joint: A systematic review. *Am J Sports Med* 2019;47:3009-3018.
10. Touhey DC, Beady ND, Tartibi S, et al. Return to sport in athletes after osteochondral allograft transplantation: A systematic review. *Am J Sports Med* published online February 20, 2025. doi:10.1177/03635465251315492
11. Wang X, Ren Z, Liu Y, et al. Characteristics and clinical outcomes after osteochondral allograft transplantation for treating articular cartilage defects: Systematic review and single-arm meta-analysis of studies from 2001 to 2020. *Orthop J Sports Med* 2023;11:23259671231199418. doi:10.1177/23259671231199418
12. Gopinatth V, Tartibi S, Smith MV, Matava MJ, Brophy RH, Knapik DM. Osteochondral allograft transplantation as a salvage procedure after failed index cartilage surgery of the knee: A systematic review. *Am J Sports Med* 2025;53:469-479.
13. Prigmore B, Haneberg E, Elias T, et al. Comparison of patient-reported outcomes for immediate unrestricted weightbearing versus restricted rehabilitation protocols after osteochondral allograft transplantation to the distal femur. *Orthop J Sports Med* 2024;12:23259671241264856. doi:10.1177/23259671241264856
14. Frank RM, Lee S, Levy D, et al. Osteochondral allograft transplantation of the knee: Analysis of failures at 5 years. *Am J Sports Med* 2017;45:864-874.
15. Assenmacher AT, Pareek A, Reardon PJ, Macalena JA, Stuart MJ, Krych AJ. Long-term outcomes after osteochondral allograft: A systematic review at long-term follow-up of 12.3 years. *Arthroscopy* 2016;32:2160-2168.
16. Chahal J, Gross AE, Gross C, et al. Outcomes of osteochondral allograft transplantation in the knee. *Arthroscopy* 2013;29:575-588.
17. Abed V, Kapp S, Nichols M, et al. Responsiveness of patient-reported outcome measures after large knee articular cartilage transplantation: A systematic review and meta-analysis. *Am J Sports Med* 2024;52:2676-2682.
18. Bi AS, Franzia CH, Mufti YN, Sachs JP, Cole BJ. Short-term patient-report outcomes following osteochondral allograft combined with concomitant knee procedures predict mid- and long-term outcomes. *Arthroscopy* published online April 8, 2025. doi:10.1016/j.arthro.2025.03.063

19. Gross AE, Shasha N, Aubin P. Long-term followup of the use of fresh osteochondral allografts for posttraumatic knee defects. *Clin Orthop* 2005;435:79-87.
20. Oakeshott RD, Farine I, Pritzker KP, Langer F, Gross AE. A clinical and histologic analysis of failed fresh osteochondral allografts. *Clin Orthop* 1988;233:283-294.
21. Bugbee WD, Pallante-Kichura AL, Görtz S, Amiel D, Sah R. Osteochondral allograft transplantation in cartilage repair: Graft storage paradigm, translational models, and clinical applications. *J Orthop Res* 2016;34:31-38.
22. Czitrom AA, Keating S, Gross AE. The viability of articular cartilage in fresh osteochondral allografts after clinical transplantation. *J Bone Joint Surg Am* 1990;72:574-581.
23. Cook JL, Stannard JP, Stoker AM, et al. Importance of donor chondrocyte viability for osteochondral allografts. *Am J Sports Med* 2016;44:1260-1268.
24. Elias TJ, Allahabadi S, Haneberg E, et al. Osteochondral allograft reaming significantly affects chondrocyte viability. *Am J Sports Med* 2024;52:2874-2881.
25. Cotter EJ, Wang KC, Yanke AB, Chubinskaya S. Bone marrow aspirate concentrate for cartilage defects of the knee: From bench to bedside evidence. *Cartilage* 2018;9:161-170.
26. Chahla J, Dean CS, Moatshe G, Pascual-Garrido C, Serra Cruz R, LaPrade RF. Concentrated bone marrow aspirate for the treatment of chondral injuries and osteoarthritis of the knee: A systematic review of outcomes. *Orthop J Sports Med* 2016;4:2325967115625481. doi:10.1177/2325967115625481
27. Gobbi A, Chaurasia S, Karnatzikos G, Nakamura N. Matrix-induced autologous chondrocyte implantation versus multipotent stem cells for the treatment of large patellofemoral chondral lesions: A nonrandomized prospective trial. *Cartilage* 2015;6:82-97.
28. Gobbi A, Karnatzikos G, Scotti C, Mahajan V, Mazzucco L, Grigolo B. One-step cartilage repair with bone marrow aspirate concentrated cells and collagen matrix in full-thickness knee cartilage lesions: Results at 2-year follow-up. *Cartilage* 2011;2:286-299.
29. Skowroński J, Skowroński R, Rutka M. Large cartilage lesions of the knee treated with bone marrow concentrate and collagen membrane—results. *Ortop Traumatol Rehabil* 2013;15:69-76.
30. Klein C, Dahmen J, Emanuel KS, Stufkens S, Kerkhoffs GMMJ. Limited evidence in support of bone marrow aspirate concentrate as an additive to the bone marrow stimulation for osteochondral lesions of the talus: A systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc* 2023;31:6088-6103.
31. Drakos MC, Hansen OB, Eble SK, et al. Augmenting osteochondral autograft transplantation and bone marrow aspirate concentrate with particulate cartilage extracellular matrix is associated with improved outcomes. *Foot Ankle Int* 2022;43:1131-1142.
32. Stoker AM, Baumann CA, Stannard JP, Cook JL. Bone marrow aspirate concentrate versus platelet rich plasma to enhance osseous integration potential for osteochondral allografts. *J Knee Surg* 2018;31:314-320.
33. Wang D, Lin KM, Burge AJ, Balazs GC, Williams RJ. Bone marrow aspirate concentrate does not improve osseous integration of osteochondral allografts for the treatment of chondral defects in the knee at 6 and 12 months: A comparative magnetic resonance imaging analysis. *Am J Sports Med* 2019;47:339-346.
34. Oladeji LO, Stannard JP, Cook CR, et al. Effects of autogenous bone marrow aspirate concentrate on radiographic integration of femoral condylar osteochondral allografts. *Am J Sports Med* 2017;45:2797-2803.
35. Ackermann J, Mestriner AB, Shah N, Gomoll AH. Effect of autogenous bone marrow aspirate treatment on magnetic resonance imaging integration of osteochondral allografts in the knee: A matched comparative imaging analysis. *Arthroscopy* 2019;35:2436-2444.
36. Dragoo JL, Guzman RA. Evaluation of the consistency and composition of commercially available bone marrow aspirate concentrate systems. *Orthop J Sports Med* 2020;8:2325967119893634. doi:10.1177/2325967119893634
37. Stone AV, Christian DR, Redondo ML, et al. Osteochondral allograft transplantation and osteochondral autograft transfer. *Oper Tech Sports Med* 2018;26:183-188.
38. Allahabadi S, Haneberg EC, Elias TJ, McMorrow KJ, Yanke AB, Cole BJ. Osteochondral allografts: Pearls to maximize biologic healing and clinical success. *Arthrosc Tech* 2023;12:e2281-e2287.
39. Gelber PE, Ramírez-Bermejo E, Grau-Blanes A, Gonzalez-Osuna A, Llauger J, Fariñas O. A new computed tomography scoring system to assess osteochondral allograft transplantation for the knee: Inter-observer and intra-observer agreement. *Int Orthop* 2021;45:1191-1197.
40. Brown D, Shirzad K, Lavigne SA, Crawford DC. Osseous integration after fresh osteochondral allograft transplantation to the distal femur: A prospective evaluation using computed tomography. *Cartilage* 2011;2:337-345.
41. Demange M, Gomoll AH. The use of osteochondral allografts in the management of cartilage defects. *Curr Rev Musculoskelet Med* 2012;5:229-235.
42. von Rechenberg B, Akens MK, Nadler D, et al. Changes in subchondral bone in cartilage resurfacing—an experimental study in sheep using different types of osteochondral grafts. *Osteoarthritis Cartilage* 2003;11:265-277.
43. Shimozono Y, Yasui Y, Hurley ET, Paugh RA, Deyer TW, Kennedy JG. Concentrated bone marrow aspirate may decrease postoperative cyst occurrence rate in autologous osteochondral transplantation for osteochondral lesions of the talus. *Arthroscopy* 2019;35:99-105.
44. Shimozono Y, Coale M, Yasui Y, O'Halloran A, Deyer TW, Kennedy JG. Subchondral bone degradation after microfracture for osteochondral lesions of the talus: An MRI analysis. *Am J Sports Med* 2018;46:642-648.
45. Imam MA, Holton J, Ernstbrunner L, et al. A systematic review of the clinical applications and complications of bone marrow aspirate concentrate in management of bone defects and nonunions. *Int Orthop* 2017;41:2213-2220.
46. Ziegler CG, Van Sloun R, Gonzalez S, et al. Characterization of growth factors, cytokines, and chemokines in bone marrow concentrate and platelet-rich plasma: A prospective analysis. *Am J Sports Med* 2019;47:2174-2187.
47. Ackermann J, Merkely G, Shah N, Gomoll AH. Decreased graft thickness is associated with subchondral cyst formation after osteochondral allograft transplantation in the knee. *Am J Sports Med* 2019;47:2123-2129.

Appendix Table 1. ACTOCA Grading by Individual Raters

Imaging Characteristic	Scoring	Grader 1	Grader 2	Grader 3	κ	*P* Value
Graft signal density	0: Equivalent	17	18	22	0.70	<.001
	1: Superior	27	26	20		
	2: Inferior	0	0	2		
Osseous integration	0: Crossing trabeculae	26	26	12	0.60	<.001
	1: Discernable cleft <3 mm	15	15	28		
	2: Discernible cleft >3 mm	3	3	4		
Surface percentage with discernible cleft	0: <30%	30	31	19	0.59	<.001
	1: >30%	14	13	25		
Cystic changes of graft and/or host-graft junction	0: absent	17	17	3	0.56	<.001
	1: present <3 mm	20	19	29		
	2: present >3 mm	7	8	12		
Intra-articular fragments	0: absent	36	38	42	0.43	<.001
	1: present	8	6	2		