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SYSTEMATIC REVIEW

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Bone Marrow Aspirate Augmentation Reduces Reoperation Rates After Osteochondral Allograft Transplantation of the Knee: A Systematic Review

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Purpose: To systematically review the clinical, radiographic, and patient-reported outcomes of osteochondral allograft (OCA) transplantation with versus without bone marrow aspirate (BMA) augmentation for the treatment of knee cartilage defects.
Methods: A comprehensive search was performed according to the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Comparative clinical studies assessing OCA with and without BMA were included. Two reviewers independently performed screening, data extraction, and methodological quality assessment using the Cochrane Risk of Bias Tool 2.0 for randomized trials and the Methodological Index for Non-Randomized Studies for nonrandomized studies.
Results: Four studies (3 Level III, 1 Level I) involving 165 knees met the inclusion criteria. The mean follow-up duration across studies ranged from 5.5 to 18.0 months. Across 2 comparative studies, BMA augmentation was associated with fewer reoperations (2.4% vs 21.9%) compared with non-BMA augmentation. Radiographic findings were heterogeneous: 1 study showed earlier integration and reduced sclerosis with BMA at 6 months, whereas 2 magnetic resonance imaging-based studies showed no differences in OCA Magnetic Resonance Imaging Scoring System scores. Computed tomography assessment in 1 trial found increased small cysts but a trend toward fewer large cysts in BMA-treated grafts. Patient-reported outcomes from 1 study showed no significant differences in International Knee Documentation Committee or Knee injury and Osteoarthritis Outcome Score for Joint Replacement scores between groups, although achievement of the Knee injury and Osteoarthritis Outcome Score for Joint Replacement minimal clinically important difference favored the BMA cohort (88% vs 55%; $P = .076$).
Conclusions: OCA transplantation augmented with BMA is associated with significantly lower reoperation rates compared with nonaugmented transplantation. Although short-term radiographic data show improved early subchondral remodeling, these findings are not consistently corroborated by magnetic resonance imaging-based scores.
Level of Evidence: Level III, systematic review of Level I and III studies.

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Fresh osteochondral allograft (OCA) transplantation is an established treatment for large articular cartilage defects of the knee in young and active patients, with reported 10-year survivorship exceeding 80%.[1,2] Despite these favorable results, graft failure remains a significant concern,[3] with rates reaching 39.4% at mid- to long-term follow-up.[2,4,5] These failures are most frequently associated with inadequate osseous integration at the graft-host interface, which can lead to graft subsidence, cystic degeneration, or subchondral plate collapse.[6] Consequently, there is increasing interest in biologic augmentation strategies designed

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to accelerate or enhance osseous healing and mitigate these failure mechanisms.[7]

Despite the theoretical benefits of BMA, the current literature is characterized by significant inconsistencies across clinical and radiographic domains. Although some investigations report expedited subchondral remodeling and a potential reduction in reoperation rates, others show no discernible difference in advanced imaging parameters or patient-reported outcome (PRO) metrics. Furthermore, reporting of adverse events and secondary surgical interventions remains variable, with conflicting data regarding the impact of biological augmentation on long-term graft survival. These disparate results highlight the need for a systematic evaluation of the efficacy of bone marrow aspirate (BMA) augmentation in OCA transplantation.

Among these strategies, BMA has emerged as a promising autologous biologic augmentation. BMA contains osteoprogenitor cells, growth factors, and anti-inflammatory cytokines that may promote both osteogenesis and chondral repair.[8,9] However, studies evaluating BMA augmentation in OCA have yielded inconsistent findings. Oladeji et al. reported that BMA-augmented femoral condylar allografts showed superior radiographic integration and reduced sclerosis at early postoperative time points.[10] In contrast, Ackermann et al. and Wang et al. found no significant improvement in osseous integration or magnetic resonance imaging (MRI)-based healing parameters with biologic augmentation use.[11,12] More recently, Yanke et al. conducted a randomized controlled trial that showed no significant difference in PROs but did find a significantly lower reoperation rate and a trend toward reduced large cyst formation in the BMA augmentation group, suggesting possible biological or anti-inflammatory effects beyond structural integration.[13] Although individual high-level studies, such as the randomized controlled trial by Yanke et al.,[13] have provided critical evidence regarding reoperation rates, the existing literature remains fragmented with small sample sizes and varied outcome measures. This systematic review expands on current knowledge by synthesizing disparate findings, such as the early radiographic integration patterns observed by Oladeji et al. alongside the more conservative MRI-based parameters reported by Wang et al.[12] and Ackermann et al.,[11] to provide a more comprehensive overview of BMA efficacy than any single primary study can offer. By aggregating these comparative data, this study aims to clarify whether biological augmentation provides a consistent clinical or structural advantage across different patient populations and surgical contexts. These disparate results highlight the need for a systematic evaluation of the efficacy of BMA augmentation in OCA transplantation.

The purpose of this study was to systematically review the clinical, radiographic, and PROs of OCA with versus without BMA augmentation for the treatment of knee cartilage defects. It was hypothesized that BMA-augmented OCA would yield improved graft incorporation and lower reoperation rates compared with nonaugmented OCA, with no significant differences in short-term PROs.

METHODS

Search Strategy

An independent and comprehensive systematic search was conducted by 2 reviewers (N.T., J.T.M.) across the PubMed, Ovid MEDLINE, and Scopus databases to identify comparative studies evaluating outcomes of OCA transplantation with versus without BMA augmentation for the treatment of focal cartilage defects of the knee. All available records from database inception through November 4, 2025, were screened. This review was performed in accordance with the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines[14] and was prospectively registered on International Prospective Register of Systematic Reviews (registration number: CRD420251239552). The search strategy incorporated the following terms: ("bone marrow aspirate concentrate" OR "bone marrow aspirate" OR "BMAC" OR "bone marrow concentrate") AND ("osteochondral allograft" OR "OCA" OR "fresh osteochondral" OR "osteochondral transplantation" OR "osteochondral graft" OR "osteochondral plug") AND ("knee" OR "femoral condyle" OR "trochlea" OR "patellofemoral joint" OR "patella" OR "tibial plateau"). Manual reference screening of all included articles was also conducted.

Eligibility Criteria

Eligible studies were required to meet the following criteria: (1) comparative clinical investigations providing Level I to III evidence, (2) publication in the English language, (3) direct comparison of OCA transplantation with versus without BMA augmentation for the management of focal cartilage defects of the knee, and (4) full-text availability. Studies were excluded if they constituted basic science or biomechanical investigations, case series or single case reports, or narrative or systematic review articles.

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Data Extraction

Study selection was independently performed by 2 reviewers (N.T., J.T.M.), who screened titles, abstracts, and full-text articles for eligibility using the Covidence platform (https://www.covidence.org/, Melbourne, Australia). Any discrepancies in study eligibility were adjudicated through consensus with a third reviewer (L.D.M.). For all studies meeting the inclusion criteria, the following variables were systematically extracted: (1) demographic characteristics, (2) level of evidence, (3) clinical characteristics of the patient cohort, (4) outcome assessment instruments, (5) surgical technique, (6) concomitant procedures, (7) postoperative rehabilitation protocols, and (8) adverse events and reoperations.

Methodological Quality Assessment

The methodological quality and risk of bias of the included studies were independently evaluated by 2 reviewers (F.C., L.D.M.). For randomized controlled trials, the Cochrane Risk of Bias Tool 2.0 was used to assess randomization processes, allocation concealment, blinding procedures, completeness of outcome data, selective outcome reporting, and other potential sources of bias.[15] For nonrandomized comparative studies, methodological quality was assessed using the Methodological Index for Non-Randomized Studies (MINORS),[16] a validated scoring instrument designed specifically for surgical research. The MINORS tool consists of 12 criteria applicable to comparative investigations. Studies scoring 0 to 12 were categorized as having low methodological quality, scores of 13 to 18 were classified as fair quality, and scores of 19 to 24 were considered good quality. All scoring was performed independently by 2 reviewers (F.C., L.D.M.), with discrepancies resolved through consensus discussion.

Statistical Analysis

All outcomes were synthesized descriptively, emphasizing ranges, proportions, and qualitative patterns across studies. Continuous and dichotomous data were summarized as reported by each study. All statistical analyses and quantitative syntheses were performed using Review Manager version 5.4 for Windows (The Cochrane Collaboration). Quantitative synthesis was performed for reoperation rates to calculate pooled odds ratios with 95% confidence intervals. Heterogeneity was assessed using the I^2 statistic, with values of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively. If the I^2 value was less than 50%, a fixed-effect model was used; if it was greater than 50%, a random-effects model was used.

RESULTS

Search Results

A total of 105 studies were identified through database searching (Scopus, PubMed, and Ovid MEDLINE). After removal of 22 duplicates, 83 studies underwent title and abstract screening, of which 72 were excluded. Eleven full-text articles were assessed for eligibility, resulting in 7 exclusions. Specific reasons for exclusion included the lack of a nonaugmented control group (n = 1), the use of alternative biologics such as platelet rich plasma as the primary intervention without a BMA comparator (n = 2), the absence of reported radiographic integration or patient-reported metrics (n = 2), and the inclusion of nonknee articular defects (n = 2) Ultimately, 4 studies[10-13] met the inclusion criteria and were selected for data extraction and analysis (Figure 1).

Included Studies

Four comparative studies[10-13] were included, comprising similar sample sizes between the BMA and non-BMA cohorts. The mean follow-up duration across studies ranged from 5.5 to 18.0 months. Three studies[10-12] were Level III evidence, and 1 study[13] was Level I evidence. Across studies, mean patient age was comparable between groups, ranging from 29.9 to 37.2 years. Mean follow-up duration was reported by 3 of the 4 studies,[11-13] ranging from 5.5 to 18.0 months with similar short-term observation between treatment arms in each study. Oladeji et al.[10] did not report mean follow-up; however, patients underwent radiographic evaluation at 6 weeks, 3 months, and 6 months. Mean body mass index values were also largely equivalent amongst studies and between groups, ranging from 26.1 to 33.2. The proportion of male patients varied among studies without a consistent pattern favoring either group (ranging from 27.3% to 76.5%) (Table 1).

Defect locations were predominantly localized to the femoral condyles, with 34 (46.6%) of the 73 patients presenting with medial femoral condyle lesions and 18 (24.7%) presenting with lateral femoral condyle lesions. Involvement of the trochlea was noted in 13 (17.8%) patients, whereas the patella was affected in 8 (11.0%) patients. The mean defect area ranged from 3.3 ± 1.0 to 4.5 ± 1.8 cm^2 across studies. Concomitant procedures varied by study; interventions included high tibial osteotomy, distal femoral osteotomy, tibial tubercle osteotomy,

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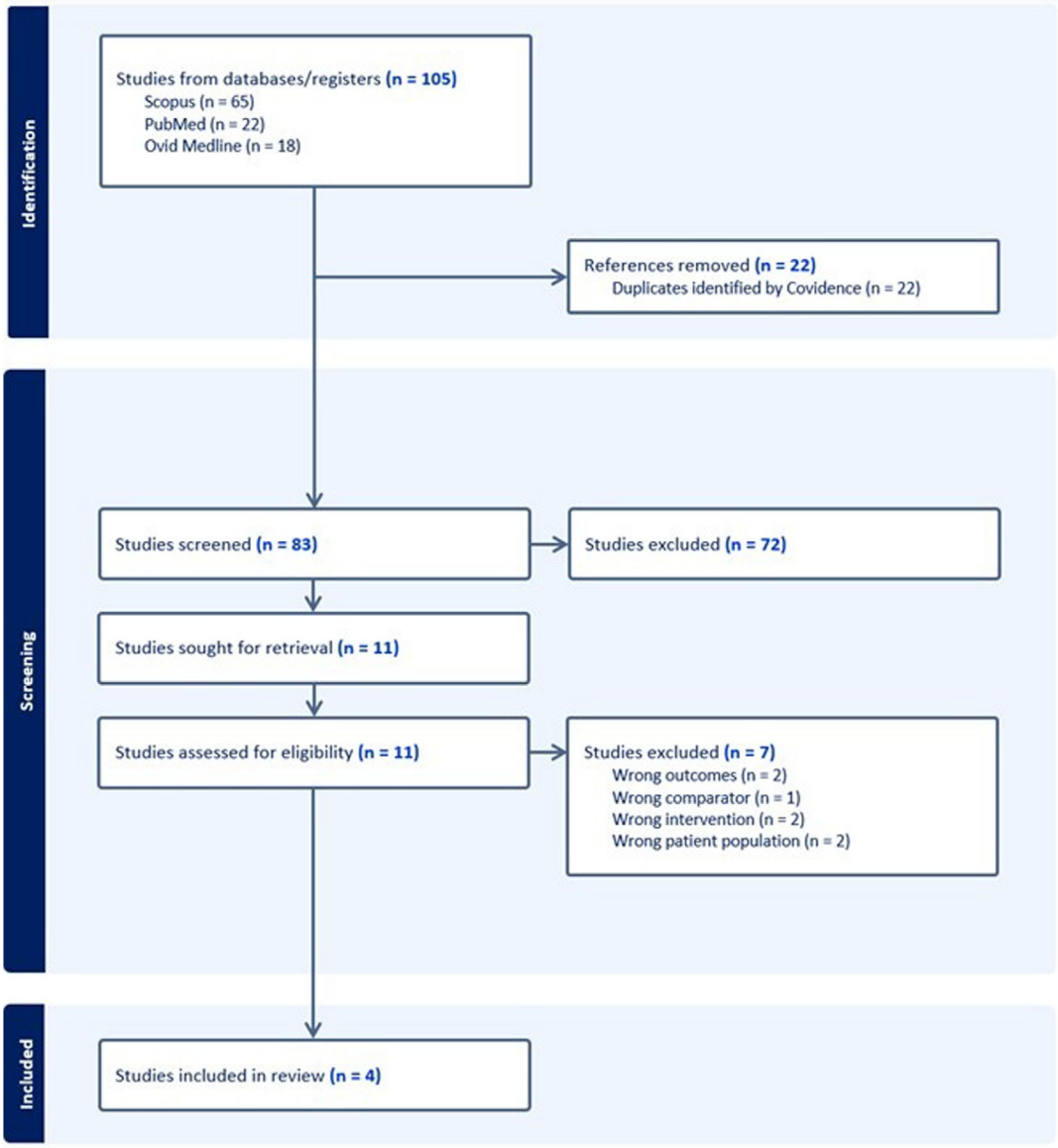

FIGURE 1 PRISMA flow diagram summarizing study selection, resulting in 4 studies included in the review. (PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.)

anterior or posterior cruciate ligament reconstruction, posterolateral corner reconstruction, medial patellofemoral ligament reconstruction, meniscus repair, meniscectomy, and meniscal allograft transplantation. PROs were inconsistently reported, with only 1 study providing International Knee Documentation Committee (IKDC) and Knee Injury and Osteoarthritis Outcome Score for Joint Replacement (KOOS JR) scores. Imaging modalities included magnetic resonance imaging, computed tomography (CT), and plain radiography to assess graft incorporation and postoperative changes. Concomitant procedures were frequent and varied significantly across the 4 studies. Reported interventions included high tibial osteotomy, distal femoral osteotomy, tibial tubercle osteotomy, anterior and posterior cruciate ligament reconstructions, medial patellofemoral ligament reconstruction, and meniscal allograft transplantation. In the study reporting most reoperations, concomitant procedures were performed in 50% of the patients (18/36). Notably, within the reoperation cohort, 5 out of the 6 failures in the non-BMA group occurred in patients who underwent the index transplantation without concomitant procedures. Conversely, the single failure in the BMA-augmented group involved a patient who had received a concomitant meniscal allograft transplantation (Table 2). The surgical technique, BMA preparation, and postoperative rehabilitation were also described (Table 3).

The surgical techniques and BMA preparation protocols used across the included studies are summarized (Table 3). Bone marrow was harvested from either the

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TABLE 1 Details of Included Studies: LOE, Sample Size, Mean Age, Mean FU, BMI, and Number of Male Patients

Lead Author (Yr)	LOE	Sample Size		Mean Age, Yr ± SD		Mean FU, Mo ± SD		Mean BMI ± SD		Male, n	
		BMA	No BMA	BMA	No BMA	BMA	No BMA	BMA	No BMA	BMA	No BMA
Ackermann (2019)[11]	III	29	29	37.2 ± 9.9	35.5 ± 10.4	5.7 ± 1.0	5.5 ± 1.0	28.6 ± 5.1	28.2 ± 5.2	17	12
Oladeji (2017)[10]	III	22	15	32.8 ± 11.9	33.4 ± 10.3	6.0	6.0	29.1 ± 5.1	33.2 ± 6.3	6	6
Wang (2019)[12]	III	18	16	35.9 ± 12.4	37.0 ± 11.1	12.3 ± 1.9	11.4 ± 1.6	27.5 ± 3.5	26.1 ± 4.4	9	12
Yanke (2025)[13]	I	19	17	34.3 ± 9.5	29.9 ± 8.8	18.0 ± 8.2	18.0 ± 8.4	27.7 ± 5.2	27.7 ± 4.2	6	13

BMA, bone marrow aspirate; BMI, body mass index; FU, follow-up; LOE, level of evidence; Mo, month; SD, standard deviation; Yr, year.

distal femoral metaphysis or the ipsilateral iliac crest. Processing methods varied significantly: 1 study used 4 mL of unprepared BMA, whereas the remaining studies were processed between 50 and 120 mL of aspirate using specialized centrifugation systems (Angel Bone Marrow Processing System or Arteriocyte Magellan) to produce 3 to 4 mL of concentrate. The resulting BMA was applied by saturating or soaking the osseous portion of the allograft for 2 to 4 minutes immediately prior to implantation.

Methodological Quality

Methodological quality assessment showed that the included randomized controlled trial by Yanke et al.[13] was evaluated using the Risk of Bias Tool 2.0 tool, which indicated "low risk" for the randomization process and deviations from intended interventions. However, "some concerns" were noted in the domains of missing outcome data and selection of the reported result, leading to an overall assessment of "some concerns" for the trial. Nonrandomized comparative studies[10-12] were assessed using the MINORS criteria, with scores ranging from 16 to 19 (maximum 24 for comparative studies). Points were consistently deducted across all 3 investigations for the lack of a prospective calculation of the study size and the absence of a blinded or unbiased assessment of the objective endpoints. Specifically, Oladeji et al.[10] (MINORS: 16) and Wang et al.[12] (MINORS: 17) were also noted for a lack of baseline equivalence between cohorts regarding certain demographic variables, whereas Ackermann et al.[11] (MINORS: 19) provided the most robust comparative design among the nonrandomized evidence.

Reoperation

Two comparative studies[10,13] reported reoperation outcomes. When these data were combined, the BMA-augmented group experienced 1 reoperation among 41 knees (2.4%), whereas the non-BMA group had 7 reoperations among 32 knees (21.9%). At the individual study level, Oladeji et al.[10] reported 0 reoperations in the BMA-augmented group (0/22) compared with 1 reoperation in the non-BMA group (1/15). Yanke et al.[13] found that patients receiving BMA were significantly less likely to require subsequent surgery for graft debridement or revision, with a reoperation rate of 5.3% (1/19) versus 35.3% (6/17) in the sham group. The pooled meta-analysis showed that BMA augmentation was associated with a statistically significantly lower risk of reoperation compared

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TABLE 2 Details of Included Studies: Location, Mean Defect Area, Concomitant Procedure, PROs, and Imaging

Lead Author (Yr)	Location, n		Mean Defect Area, cm^2 ± SD		Concomitant Procedures, n		PROs Reported	Imaging
	BMA	No BMA	BMA	No BMA	BMA	No BMA		
Ackermann (2019)[11]	- MFC: 20	- MFC: 20	3.3 ± 1.0		- MPFLR: 1	- HTO: 2	NR	MRI
	- LFC: 5	- LFC: 5			- MAT: 1	- ACLR: 2		
	- Trochlea: 4	- Trochlea: 4				- TTO: 2		
						- MAT: 1		
Oladeji (2017)[10]	- MFC: 18	- MFC: 9	3.3 ± 1.3	3.5 ± 1.6	- HTO: 2	- HTO: 4	NR	Plain radiograph
	- LFC: 11	- LFC: 8			- ACLR: 1	- ACLR: 1		
	- Trochlea: 0	Trochlea: 0			- MAT: 8	- PCLR: 1		
					- DFO: 1	- PLCR: 1		
					- Meniscectomy: 1	- MAT: 6		
Wang (2019)[12]	- MFC: 6	- MFC: 8	3.9 ± 1.9	4.5 ± 1.8	Excluded all concomitant intra-articular procedures	Excluded all concomitant intra-articular procedures	NR	MRI
	- LFC: 8	- LFC: 4						
	- Trochlea: 5	- Trochlea: 4						
Yanke (2025)[13]	- MFC: 10	- MFC: 10	NR	NR	- HTO: 1	- ACLR: 2	IKDC, KOOS JR	CT
	- LFC: 6	- LFC: 4			- ACLR: 1	- MPFLR: 1		
	- Trochlea: 2	- Trochlea: 3			- MPFLR: 2	- TTO: 2		
	- Patella: 6	- Patella: 2			- TTO: 4	- MAT: 2		
					- MAT: 2	- Meniscectomy: 1		
					- DFO: 1			
					- Root repair: 1			

ACLR, anterior cruciate ligament reconstruction; BMA, bone marrow aspirate; CT, computed tomography; DFO, distal femoral osteotomy; HTO, high tibial osteotomy; IKDC, International Knee Documentation Committee; KOOS JR, Knee Injury and Osteoarthritis Outcome Score for Joint Replacement; LFC, lateral femoral condyle; MAT, meniscal allograft transplantation; MFC, medial femoral condyle; MPFLR, medial patellofemoral ligament reconstruction; MRI, magnetic resonance imaging; NR, not reported; PCLR, posterior cruciate ligament reconstruction; PLCR, posterolateral corner reconstruction; PROs, patient-reported outcomes; SD, standard deviation; TTO, tibial tubercle osteotomy; Yr, year.

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TABLE 3 Details of Included Studies: Surgical Technique, BMA Preparation, and Postoperative Rehabilitation

Lead Author (Yr)	Surgical Techniques	BMA Preparation	Postoperative Rehabilitation
Ackermann (2019)[11]	- Graft: fresh OCAs, harvested within 24 hours, screened, matched, and stored at 4°C	- Harvest site: distal femoral metaphysis	- Weight-bearing: touch-down weight-bearing for 4 weeks
	- Approach: small parapatellar arthrotomy	- Volume: 4 mL	- ROM: CPM initiated on postoperative day 3, progressing to 90°
	- Defect preparation: reamed (5-8 mm) using a dowel technique	- Centrifuge: unprepared BMA	- Return to activity: 6 months
	- Graft preparation: pulse-lavage and beveled	- Application: saturate the graft's subchondral bone	
	- Fixation: manual press-fit		
Oladeji (2017)[10]	- Graft: large cylindrical fresh OCAs defined as $> 2.5\ cm^2$ defect (1-3 per condyle) or shell fresh OCAs (1 per condyle)	- Harvest site: distal femoral metaphysis	- Weight-bearing: NR
	- Approach: NR	- Volume: 80 to 120 mL	- ROM: NR
	- Defect preparation: NR	- Centrifuge: Angel Bone Marrow Processing System (Arthrex)	- Return to activity: NR
	- Graft preparation: power irrigation with normal saline	- Application: 2-minute saturation of the graft's subchondral bone	
	- Fixation: NR		
Wang (2019)[12]	- Graft: fresh OCAs	- Harvest site: ipsilateral iliac crest	- Weight-bearing: touch-down weight-bearing for 1 week in hinged knee brace and then progression to full weight-bearing as tolerated
	- Approach: NR	- Volume: 50 mL harvested, 3 to 4 mL BMAC	- ROM: active-assisted ROM, immediate full ROM with CPM, hinged knee brace for minimum of 2 weeks
	- Defect preparation: reamed (6-10 mm) using a dowel technique	- Centrifuge: Arteriocyte (Magellan)	- Return to activity: 6 months
	- Graft preparation: NR	- Application: 4-minute saturation of the graft's subchondral bone; application of 1 to 2 mL BMAC to the defect bed prior to graft implantation	

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TABLE 3 (Continued)

Lead Author (Yr)	Surgical Techniques	BMA Preparation	Postoperative Rehabilitation
	- Fixation: manual press-fit using dowel for 1 OCA graft; snowman configuration for 2 OCA grafts		
Yanke (2025)[13]	- Graft: fresh OCAs	- Harvest site: ipsilateral iliac crest	- Weight-bearing: NR
	- Approach: parapatellar arthrotomy	- Volume: 60 mL harvested, 3 to 4 mL BMAC	- ROM: NR
	- Defect preparation: reamed (6-8 mm) using a dowel technique	- Centrifuge: Angel Bone Marrow Processing System (Arthrex)	- Return to activity: NR
	- Graft preparation: pulse lavage or pressurized carbon dioxide systems	- Application: 2-minute soak of the graft	
	- Fixation: manual press-fit		

BMA, bone marrow aspirate; BMAC, bone marrow aspirate concentration; CPM, continuous passive motion; NR, not reported; OCA, osteochondral allograft; ROM, range of motion; Yr, year.

with the non-BMA group (odds ratio, 0.13; 95% confidence interval, 0.02-0.80; $P = .03$). Analysis of study heterogeneity revealed the I^2 value of 0%, indicating negligible statistical heterogeneity between the 2 trials (Figure 2).

Radiographic Outcomes

Radiographic assessment across the included studies showed no consistent advantage of BMA augmentation in early graft incorporation or subchondral remodeling (Table 4).

Ackermann et al.[11] used the OCA MRI Scoring System (OCAMRISS) to descriptively assess graft integration. The study found no significant differences between the BMA and non-BMA groups regarding osseous, cartilage, or ancillary subscores. Although most patients in both cohorts achieved high scores for cartilage signal, fill, and osseous integration, parameters such as cartilage integration and subchondral bone congruity showed comparable rates of disruption or incomplete flush boundaries across groups ($P > .05$ for all subscores). Notably, the graft's calcified cartilage integrity was not assessed owing to the lack of specialized ultrashort-echo time MRI sequences.

In contrast, Oladeji et al.[10] reported serial radiographic assessments at 6 weeks, 3 months, and 6 months after OCA transplantation with or without BMA augmentation. OCAMRISS scoring was not provided because no MRI was performed, but plain radiographs showed similar early graft integration patterns between the 2 groups at all time points. At 6 weeks, the mean graft integration percentage was 43.1 ± 22.8 in the BMA group compared with 25.6 ± 25.0 in the non-BMA group ($P = .03$). By 3 months, integration progressed to 67.2 ± 17.9 versus 50.6 ± 28.9, respectively ($P = .033$), and by 6 months, it reached 84.1 ± 8.4 versus 74.4 ± 15.9 ($P = .017$). Graft sclerosis scores were likewise comparable. At 6 weeks, sclerosis measured 1.4 ± 0.6 in the BMA group and 1.9 ± 0.6 in the non-BMA group ($P = .016$). Scores decreased at 3 months (1.2 ± 1.2 vs 1.7 ± 0.7; $P = .017$) and further at 6 months (0.9 ± 0.9 vs 1.2 ± 0.5; $P = .20$). Overall, radiographic findings indicated gradual remodeling with statistically significantly earlier subchondral integration and less sclerosis associated with BMA augmentation.

Wang et al.[12] provided quantitative MRI evaluation using OCAMRISS subscores and total score. The BMA group showed mean bone, cartilage, and ancillary subscores of 2.7 ± 0.8, 3.1 ± 1.2, and 2.5 ± 1.2, respectively, resulting in a total OCAMRISS score of 8.3 ± 2.6. The non-BMA group showed nearly identical

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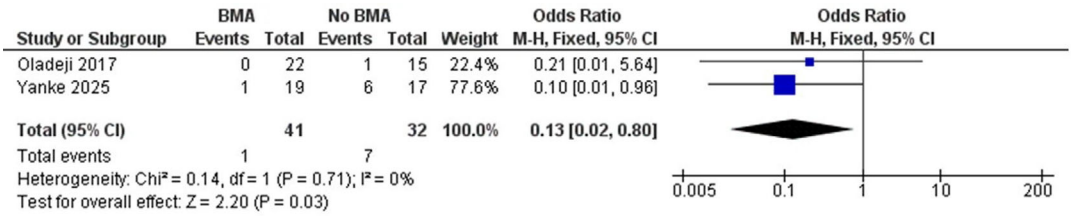

FIGURE 2 Forest plot comparing reoperation rates between BMA-augmented and nonaugmented osteochondral allograft transplantation. (BMA, bone marrow aspirate; CI, confidence interval; M-H, Mantel-Haenszel.)

values, with bone, cartilage, and ancillary subscores of 2.9 ± 0.8, 3.1 ± 1.7, and 2.4 ± 1.1, and a total score of 8.4 ± 2.5. These findings indicated no statistically significant difference in early graft osseous integration ($P = .97$), cartilage signal characteristics ($P = .44$), ancillary MRI features ($P = .83$), or total OCAMRISS score ($P = .90$) between BMA-augmented and nonaugmented OCA grafts.

Yanke et al.[13] evaluated postoperative CT scans and reported no differences between groups in most of the CT-based categories. However, the study did find a significant increase in the number of small cysts (<3 mm) in the BMA group ($P = .03$) along with a trend toward reduced large cyst (>3 mm) formation ($P = .06$), suggesting a possible shift in cyst morphology but without clear evidence of improved healing.

Overall, radiographic findings across MRI, radiograph, and CT modalities showed comparable graft incorporation, sclerosis, and subchondral changes between the BMA and non-BMA groups in the early postoperative period.

PRO Scores

Only 1 study by Yanke et al.[13] provided quantitative PROs comparing OCA with and without BMA augmentation. At 2-year follow-up, the BMA group showed mean IKDC and KOOS JR scores of 64.9 ± 24.1 and 73.6 ± 13.6, respectively, whereas the non-BMA group showed IKDC and KOOS JR scores of 63.4 ± 18.1 and 74.9 ± 18.6 ($P = .71$ and $P = .95$, respectively). These values indicate no statistically significant differences in functional outcomes between groups. Additionally, the proportions of patients achieving the minimal clinically important difference (MCID) were comparable between groups. MCID for the IKDC was reached in 81% of the BMA cohort and 75% of the non-BMA group ($P = .99$). For the KOOS JR, MCID was achieved in 88% of patients in the BMA group compared with 55% in the non-BMA group ($P = .076$).

DISCUSSION

The primary finding of this study is that BMA augmentation of OCA transplantation in the knee is associated with a significantly lower reoperation rate compared with nonaugmented transplantation. Furthermore, meta-analysis of the available data showed that BMA-treated grafts have a reduced risk of failure requiring surgical intervention. Radiographic assessment across the included literature suggests that although BMA may be associated with earlier osseous integration and reduced subchondral sclerosis on plain radiographs, these findings are not consistently corroborated by advanced imaging modalities. Finally, PROs did not differ between groups. It is important to note that this finding is derived exclusively from the study by Yanke et al.,[13] which remains the only investigation to provide quantitative functional scores for this comparison.

Incomplete graft osseous integration is a primary driver of OCA failure and reoperation, with long-term reoperation rates reported as high as 39.4%.[2,3,5] Although this study suggests that biological augmentation with BMA may mitigate these risks by enhancing subchondral remodeling, these findings are derived largely from a single randomized controlled trial.[2] Consequently, the reliance on data from a single institution limits the current generalizability of these positive outcomes despite promising consistency with available cohort data. Given the high reoperation rates, Kunze et al.[5] further characterized risk factors for failure with a recent 2024 systematic review and meta-analysis. They found that bipolar chondral defects, patellar defects, male sex, higher BMI, and older age significantly increased the odds that an OCA graft would fail, citing a possible link between limited biological graft incorporation and these risk factors.[5] In this systematic review, the 2 available comparative studies[10,13] were associated with consistently lower reoperation rates in knees treated with BMA-augmented OCA transplantation. Although the consistently lower reoperation rates suggest a potential protective effect of biological augmentation, the evidence is limited by a small number of comparative

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TABLE 4 Radiographic Outcomes After Osteochondral Allograft Transplantation With and Without BMA Concentrate Augmentation

Lead Author (Yr)	OCAMRISS (BMA) Mean ± SD	OCAMRISS (No BMA) Mean ± SD	Radiographic Integration (BMA) Mean ± SD	Radiographic Integration (No BMA) Mean ± SD	Graft Sclerosis (BMA) Mean ± SD	Graft Sclerosis (No BMA) Mean ± SD	Notes
Ackermann (2019)[11]	NR (MRI features described as n per category instead of a score; no differences identified)	NR (MRI features described as n per category instead of a score; no differences identified)	NR	NR	NR	NR	MRI: no group differences reported
Oladeji (2017)[10]	NR	NR	6 wk: 43.1 ± 22.8	6 wk: 25.6 ± 25.0	6 wk: 1.4 ± 1.3	6 wk: 1.9 ± 0.6	Radiographs performed, no quantitative scoring
			3 mo: 67.2 ± 17.9	3 mo: 50.6 ± 28.9	3 mo: 1.2 ± 1.2	3 mo: 1.7 ± 0.7	
			6 mo: 84.1 ± 8.4	6 mo: 74.4 ± 15.9	6 mo: 0.9 ± 0.9	6 mo: 1.2 ± 0.5	
Wang (2019)[12]	Bone: 2.7 ± 0.8	Bone: 2.9 ± 0.8	NR	NR	NR	NR	MRI scores nearly identical between groups
	Cartilage: 3.1 ± 1.2	Cartilage: 3.1 ± 1.7					
	Ancillary: 2.5 ± 1.2	Ancillary: 2.4 ± 1.1					
	Total: 8.3 ± 2.6	Total: 8.4 ± 2.5					
Yanke (2025)[13]	NR	NR	NR	NR	NR	NR	CT: ↑ small cysts <3 mm in BMAC ($P = .03$); ↓ trend in large cysts ($P = .06$)

BMA, bone marrow aspirate; BMAC, bone marrow aspirate concentration; CT, computed tomography; mo, month; MRI, magnetic resonance imaging; NR, not reported; OCA, osteochondral allograft; OCAMRISS, Osteochondral Allograft Magnetic Resonance Imaging Scoring System; SD, standard deviation; wk, week; Yr, year.

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studies and short-term follow-up. Furthermore, the lack of a concentration step in some BMA protocols may reduce the density of osteogenic proteins and cells available to populate the subchondral scaffold, potentially influencing the speed of integration.[11] Although the observed reduction in reoperations is promising, it is primarily driven by a single study. Future large-scale randomized trials are necessary to confirm long-term durability. These studies should use standardized reporting for PROs, reoperations, and radiographic metrics, with adequate minimum follow-up periods to ensure data consistency. Significant heterogeneity in radiographic assessment remains a primary obstacle to drawing definitive conclusions regarding the biological impact of BMA on OCA integration.[17] The included studies used disparate imaging modalities, ranging from serial plain radiography and CT to advanced MRI scoring systems (OCAMRISS), each evaluating distinct biological characteristics of subchondral and cartilage healing.[10] Although standard OCA transplantation without augmentation eventually achieves high rates of incorporation at 2 years, the lack of standardized early assessment protocols makes it difficult to verify if BMA truly accelerates this timeline. For instance, although Oladeji et al.[10] observed significantly faster osseous integration and reduced sclerosis on radiographs, Ackermann et al.[3] and Wang et al.[12] found no discernible differences using MRI-based metrics at 6 and 12 months. These inconsistencies suggest that although biological augmentation may influence early subchondral remodeling, its impact on the overarching structural environment remains unproven across varied imaging platforms. Consequently, although current imaging data regarding reduced cyst formation and improved cartilage filling are encouraging, they highlight a critical need for standardized, prospective radiographic surveillance to evaluate long-term durability.

Despite the lower reoperation rates and potentially faster integration of BMA-augmented OCA grafts, PROs did not differ between groups at any time point over a 2-year follow-up. Notably, Yanke et al.[13] was the only study to compare PROs for patients receiving BMA-augmented OCAs versus those with nonaugmented grafts, and only 36 patients (19 BMA-augmented and 17 control patients) were included. IKDC and KOOS JR scores at final 2-year follow-up (64.9 ± 24.1 and 73.6 ± 13.6, respectively) for the patients receiving BMA augmentation all met MCID and were vastly comparable to other literature on OCA outcomes without BMA augmentation.[2,17-22] It is notable that the percentage of patients reaching MCID for KOOS JR (88% for BMA-augmented and 55% for controls, $P = .076$) trended toward statistical significance.[13] Data regarding PROs remain sparse because only 1 study provided quantitative comparisons for this metric. Additionally, there is currently a paucity of evidence comparing BMA-augmented grafts to alternative biological techniques, such as platelet-rich plasma or mesenchymal stem cells. Future studies on PROs in this patient population should evaluate a larger patient sample size and focus on long-term outcomes to determine the clinical significance of using BMA as a biological augmentation for OCA transplantation.

Although these findings suggest a potential protective effect of biological augmentation, the authors acknowledge that the conclusions regarding reoperation and functional outcomes are heavily weighted by the findings of a single high-level randomized trial.[13] Although the consistency between this trial and available retrospective data is encouraging, the lack of multi-institutional prospective data limits the broader applicability of these findings.

Limitations

There are several limitations inherent to this systematic review. The low number of published comparative studies precluded the performance of a meta-analysis for radiographic outcomes and PROs. High heterogeneity in imaging modalities, including MRI, plain radiographs, and CT scans, prevented standardized comparisons of chondral and osseous integration. Additionally, inconsistent OCAMRISS score reporting and the absence of calcific cartilage evaluation because of MRI sequence limitations precluded further quantitative analysis. Meaningful comparisons between OCAMRISS scores from Ackermann et al.[11] and Oladeji et al.[10] were limited owing to differences in BMA and BMA augmentation. Importantly, the lack of a concentration step in BMA preparation may reduce the number of osteogenic proteins and cells available to populate the graft's subchondral bone scaffold.[7] In addition, differences in evaluation of calcific cartilage because of clinical MRI limitations and inconsistent OCAMRISS score reporting styles precluded additional analysis. Imaging modalities included MRI,[10,11] plain radiographs,[12] and CT scans,[13] preventing standardized comparisons and limiting conclusions about chondral and osseous integration of OCA grafts because each modality evaluates these differently. Additionally, PROs were only reported by Yanke et al.'s randomized controlled trial of 36 patients,[13] thus limiting the generalizability and clinical applicability of these findings. Reoperation rates were reported by 2 studies; however, a meta-analysis was not performed because of small-study bias and limited statistical rigor provided by the low study count. The relatively large variability in concomitant operations with OCA transplantation in the included studies adds heterogeneity and introduces potential confounding that cannot be accounted for. Furthermore, in accordance with the Sex

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and Gender Equity in Research guidelines, it must be noted that none of the included investigations reported outcomes disaggregated by sex. Given that sex-based differences in bone metabolism and stem cell potency may influence graft integration, the lack of gender-specific data limits the ability to provide personalized clinical recommendations and represents a significant gap in the current OCA literature.

CONCLUSIONS

OCA transplantation augmented with BMA is associated with significantly lower reoperation rates compared with nonaugmented transplantation. Although short-term radiographic data show improved early subchondral remodeling, these findings are not consistently corroborated by MRI-based scores.

DISCLOSURES

The authors (A.B.Y., B.J.C., J.C.) declare the following financial interests/personal relationships which may be considered as potential competing interests: A.B.Y. has received consulting fees from Stryker, JRF Ortho, and Olympus America; nonconsulting fees from Arthrex; education payments from Medwest Associates; and honoraria from JRF Ortho. B.J.C. has received consulting fees from Aesculap Biologics, Arthrex, Bioventus, DJO, Vericel, Acumed, Anika Therapeutics, OSSIO, and Pacira Pharmaceuticals; nonconsulting fees from Terumo BCT; royalties from Arthrex; hospitality payments from GE Healthcare; and honoraria from Vericel. J.C. reports relationships with American Orthopaedic Society for Sports Medicine, Arthroscopy Association of North America, and International Society of Arthroscopy Knee Surgery and Orthopaedic Sports Medicine that include board membership; Arthrex, CONMED, RTI Surgical, and Vericel that include consulting or advisory; and Smith & Nephew that include consulting or advisory and speaking and lecture fees. The other authors (N.T., J.T.M., F.C., L.D.M.) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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REFERENCES

1. Wang T, Bugbee WD. Osteochondral allograft transplantation. *Clin Sports Med.* 2025;44:553-564.
2. Gilat R, Haunschild ED, Huddleston HP, et al. Osteochondral allograft transplant for focal cartilage defects of the femoral condyles: Clinically significant outcomes, failures, and survival at a minimum 5-year follow-up. *Am J Sports Med.* 2021;49:467-475.
3. 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.
4. Wang T, Dees RL, Görtz S, McCauley JC, Bugbee WD. Clinical factors affecting outcomes of osteochondral allograft transplantation: A multivariable analysis of 560 knees. *Am J Sports Med.* 2025;53:2415-2422.
5. Kunze KN, Ramkumar PN, Manzi JE, Wright-Chisem J, Nwachukwu BU, Williams RJ 3rd. Risk factors for failure after osteochondral allograft transplantation of the knee: A systematic review and exploratory meta-analysis. *Am J Sports Med.* 2023;51:1356-1367.
6. Thamrongskulsiri N, Limskul D, Tanpowpong T, Kuptniratsaikul S, Itthipanichpong T. Clinical improvement but substantial arthroplasty risk following fresh osteochondral allograft transplantation of the femoral head: A systematic review and single-arm meta-analysis. *Knee Surg Sports Traumatol Arthrosc.* 2026;34:2224-2235.
7. 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.
8. Han JH, Jung M, Chung K, Jung SH, Choi CH, Kim SH. Bone marrow aspirate concentrate injections for the treatment of knee osteoarthritis: A systematic review of randomized controlled trials. *Orthop J Sports Med.* 2024;12:23259671241296555.
9. Jawanda H, Khan ZA, Warrier AA, et al. Platelet-rich plasma, bone marrow aspirate concentrate, and hyaluronic acid injections outperform corticosteroids in pain and function scores at a minimum of 6 months as intra-articular injections for knee osteoarthritis: A systematic review and network meta-analysis. *Arthroscopy.* 2024;40:1623-1636.e1.
10. 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.
11. 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.
12. Wang D, Lin KM, Burge AJ, Balazs GC, Williams RJ 3rd. 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.
13. Yanke AB, Dandu N, Bodendorfer BM, et al. Bone marrow aspirate concentrate may decrease reoperation in osteochondral allograft transplantation: A prospective, randomized, double-blind investigation. *Arthroscopy.* 2025;41:4664-4673.

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14. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ.* 2021;372:n71.
15. Sterne JAC, Savović J, Page MJ, et al. RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ.* 2019; 366:l4898.
16. Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological index for non-randomized studies (MINORS): Development and validation of a new instrument. *ANZ J Surg.* 2003;73:712-716.
17. Familiari F, Cinque ME, Chahla J, et al. Clinical outcomes and failure rates of osteochondral allograft transplantation in the knee: A systematic review. *Am J Sports Med.* 2018;46:3541-3549.
18. Gherghel R, Onu I, Onu A, et al. Enhancing bone-cartilage interface healing in osteochondral autograft transplantation: Effects of BMAC augmentation and rehabilitation protocols. *Life (Basel).* 2025;15:1066.
19. Nassar JE, Guerin G, Keel T, et al. Autologous chondrocyte implantation, matrix-induced autologous chondrocyte implantation, osteochondral autograft transplantation and osteochondral allograft improve knee function and pain with considerations for patient and cartilage defects characteristics: A systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc.* 2025;33:2745-2762.
20. Wang T, Gao SL, McCauley JC, Densley SM, Bugbee WD. Outcomes after osteochondral allograft transplantation of the medial femoral condyle in patients with varus and nonvarus alignment. *Am J Sports Med.* 2024;52:3013-3020.
21. Xie JF, Jackson GR, Childers JT, et al. Variable return-to-sport rates with improved pain and patient-reported outcomes following osteochondral allograft transplantation: A systematic review. *J Knee Surg.* 2025;38:563-574.
22. Cole BJ, Mufti Y, Sachs J, et al. An update on osteochondral allograft transplantation. *Sports Med Arthrosc Rev.* 2025;33:155-163.

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