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Bone-marrow-based augmentation in rotator cuff repair—from microfracture to bone marrow aspirate concentrate

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Abstract

Rotator cuff tears are a major cause of shoulder dysfunction, and relatively high rates of rotator cuff re-tear persist despite surgical advancements, particularly in patients with poor biological healing potential. Bone-marrow-based augmentation techniques, specifically bone marrow stimulation (BMS) and bone marrow aspirate concentrate (BMAC), have been introduced to enhance the biological environment at the repair site, potentially improving outcomes. Bone marrow stimulation, commonly achieved through microfracture, stimulates the release of growth factors and mesenchymal stem cells (MSCs) from the bone marrow to promote tendon-to-bone integration. Although simple and cost-effective, clinical results for BMS augmentation in rotator cuff repair (RCR) are mixed, with most recent meta-analyses not demonstrating a clinically significant superiority over conventional RCR. Augmentation with BMAC offers a more sophisticated approach, concentrating MSCs and anti-inflammatory cytokines to directly enhance the healing process. Preclinical studies have shown promising results with BMAC augmentation, demonstrating improved tendon integrity and biomechanical strength. The existing clinical studies suggest BMAC may reduce re-tear rates and enhance tendon healing, although outcomes are not yet universally optimal. The current evidence highlights the potential of these techniques, particularly as a potential treatment option in biologically challenging cases. However, the variability in clinical outcomes underscores the need for further research to refine these methods and establish their role in routine clinical practice.

Keywords
Bone marrow stimulation · Biological augmentation · Orthobiologics · Mesenchymal stem cells · Shoulder

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Rotator cuff tears (RCTs) are a major cause of disability, with a prevalence of 30% in individuals aged 60 years and older [1]. Biomechanically, RCTs lead to superior humeral head migration, shift of the glenohumeral center of rotation, disruption of rotator cuff and deltoid muscle synergy, increased glenohumeral contact loads, and premature cartilage degeneration [2]. Functionally, these deficits manifest in pain, loss of function, and early onset of cuff arthropathy [3]. Given the critical need for long-lasting structural and functional integrity of the rotator cuff for shoulder function [4], as well as the substantial potential for both short- and long-term disability [5], appropriate diagnosis and treatment of RCTs are paramount. Thus,

an array of various factors including injury etiology, symptom chronicity, healing potential, preoperative activity level, and long-term expectations should be considered carefully for the optimal treatment in this patient population [6].

The treatment principles for RCTs vary depending on the type and severity of the tear, as well as on the patient's age and functional demands; the full details go beyond the scope of this review. Briefly, conservative management is often recommended for partial-thickness tears or asymptomatic full-thickness tears, particularly in older patients who have developed compensatory mechanisms to maintain function [3]. By contrast, operative rotator cuff repair (RCR) is typically advised for full-thickness tears that are deemed repairable, especially in younger patients or those with higher functional demands, where restoring full shoulder function is crucial [7]. The current gold standard for classic posterosuperior full-thickness tears now includes the arthroscopic double-row transosseous-equivalent repair technique in a linked-construct fashion, which can be adapted based on the tendon affected, the tear size, and the tear configuration [7].

While advances in the surgical management of RCTs over the past 20 years have significantly improved patient outcomes, the revision rates for RCR still remain a concern. Systematic reviews indicate that re-tear rates are as high as 21% at 2 years postoperatively [8], depending on factors such as tear size, patient age, and the specific surgical technique employed.

In this context, augmentation strategies have garnered increasing interest, particularly in cases where the biological environment is suboptimal due to characteristics such as chronic tears, poor tendon quality, or systemic issues like advanced age and comorbidities. Augmentation techniques are broadly categorized into structural and biological methods, each with distinct roles in enhancing the repair process and improving clinical outcomes.

Structural augmentation

Structural augmentation is primarily employed to provide additional mechanical support to the RCR. This approach is particularly useful in cases where the tendon tissue is severely compromised. Structural augmentation typically involves the use of patches, which can be categorized into autografts (such as the long head of the biceps tendon), allografts (i.e., human dermal allografts), and synthetic patches (i.e., polytetrafluoroethylene).

Biological augmentation

Biological augmentation aims to enhance the intrinsic healing capacity of the RCR site, particularly in biologically inferior situations. This approach is crucial in patients with compromised healing potential due to chronic pathology, suboptimal tendon quality, or the need for revision surgeries. Beyond bone-marrow-based procedures such as bone marrow aspirate concentrate (BMAC) augmentation and bone marrow stimulation (BMS), biological augmentation techniques prominently include platelet-rich plasma (PRP; [9])—a blood concentrate rich in growth factors that stimulate cellular proliferation, angiogenesis, and tissue regeneration, thereby enhancing the healing process. Further augmentation can be performed utilizing subacromial bursa tissue, known for its high concentration of mesenchymal stem cells (MSCs), a dense fibrovascular network, and neovascularizing signals that support tissue repair and regeneration, which can be processed at the point of care and applied to the RCR site [10]. These augmentation strategies, when appropriately indicated and applied, hold the promise of improving the biological environment of RCR, reducing re-tear rates and thus optimizing postoperative outcomes.

Biological environment of rotator cuff repair

For the surgeon aiming to optimally identify a patient at risk of RCR failure, who may particularly benefit from biological augmentation, it is crucial to understand the biological processes of healing and thus to be capable of analyzing whether certain identified factors are modifiable through biological augmentation.

The native enthesis of the rotator cuff, situated at the tendon–bone junction, features a complex four-layered structure transitioning from tendon to fibrocartilage to mineralized fibrocartilage, and finally to bone [11, 12]. This configuration enables the rotator cuff to withstand the forces exerted on it during daily activities [12]. Upon injury, healing begins with an influx of pro-inflammatory cytokines (such as vascular endothelial growth factor [VEGF], insulin-like growth factor [IGF], platelet-derived growth factor [PDGF], and transforming growth factor beta [TGF-β]), macrophages/mononucleated cells, leukocytes, and neutrophils, enhancing an inflammatory cascade [9]. The reparative phase follows, characterized by the development of angiogenesis and the deposition of extracellular matrix/collagen type III [9]. The remodeling stage then ensues, involving collagen type I deposition and tissue contraction, ultimately leading to scar tissue formation [9].

It is well established that enthesis regeneration is not yet optimally enhanced by current RCR strategies [11, 13]. Although these strategies achieve re-approximation of the injured tendon to its bony footprint, they predominantly induce the formation of scar tissue, which possesses inferior mechanical properties to the native state [12, 14]. The current onlay augmentation methods (placing scaffolds on top of the repaired tendon) have also failed to recreate the native four-layered enthesis (**Fig. 1**, [12, 15]).

Importance of biological healing

Multiple patient-specific and injury-specific factors have been validated as prognostic indicators of rotator cuff re-tear through large-scale clinical studies. In the context of these factors, cases with inferior healing potential that may benefit from biological augmentation can be identified by a concise patient-specific analysis [16, 17]. Patient-specific prognostic factors for healing include age, sex, bone mineral density, level of work activity, and medical comorbidities [12, 17, 18]. On the other hand, tear-specific factors include tear chronicity, anteroposterior tear size, extent of tendon retraction, remaining tendon stump length, atrophy of the tendon, and degree of fatty infiltration [12, 17, 18]. Studies deriving these prog-

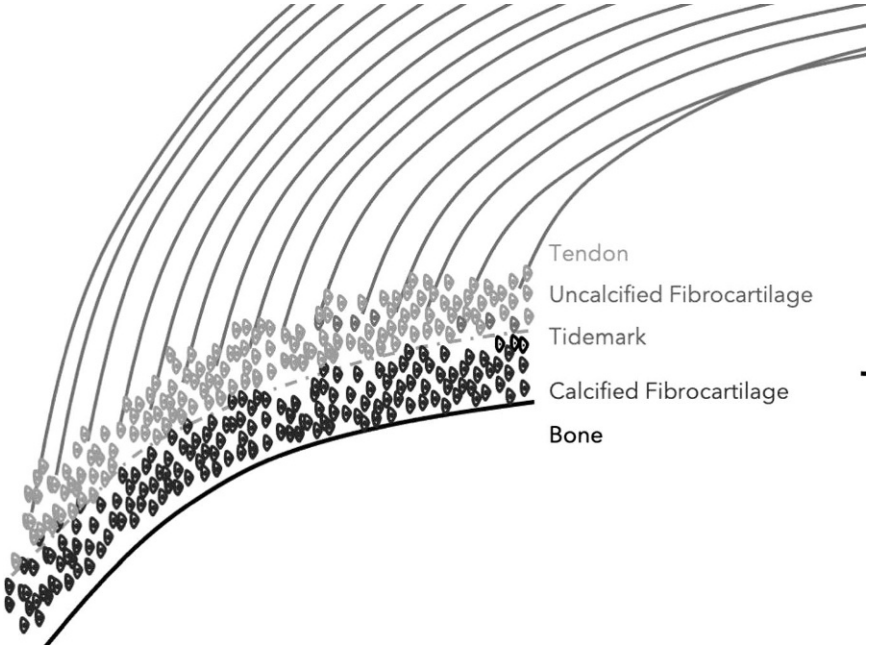

Fig. 1 ▲ Depiction of the multilayered tendon–bone interface of the rotator cuff, highlighting zones from tendon to bone: tendon, uncalcified fibrocartilage, "tidemark," calcified fibrocartilage, and bone. The gradient structure facilitates smooth transition, load distribution, stress reduction, and effective integration of tendon to bone

nostic variables are typically conducted via clinical imaging assessing short-term postoperative rotator cuff re-tear. However, recent animal models have shown that despite a "healed" and intact rotator cuff tendon, healing at the tendon–bone interface is often driven by scar tissue formation rather than by enthesis reformation [12, 17]. Given the weaker tissue biomechanics of scar tissue relative to an enthesis, efforts have shifted toward enhancing true rotator cuff tendon–bone healing via enthesis reconstruction through biological augmentation options.

Bone-marrow-based biological augmentation

As briefly introduced earlier, bone-marrow-based augmentation in RCR aims to enhance healing at the tendon–bone interface by utilizing the regenerative potential of bone-marrow-based MSCs. The rationale is to introduce MSCs and growth factors to the repair site in order to promote better tissue regeneration and tendon–bone integration. The two key techniques used are BMS, which involves creating small perforations in the bone to release marrow elements and stimulate healing, and BMAC, which involves harvesting and concentrating bone marrow to directly apply MSCs and growth factors to the repair site. Both techniques will be discussed in more detail.

Bone marrow stimulation

Biological principles

Augmentation of rotator cuff tendon repairs via BMS—such as microfracture or nanofracture at the greater tuberosity—is a simple yet cost-effective surgical technique that has gained popularity in sports medicine. Although the use of microfracture on the articular surface for chondral lesions has shown suboptimal long-term outcomes due to fibrocartilage formation [19, 20], BMS has demonstrated more promising results when utilized at the greater tuberosity for biological augmentation of the tendon–bone interface [21, 22]. Animal studies using rat models have shown thicker tendon width postoperatively among healed tendons, improved collagen organization and tendon–bone interface reformation, and improved biomechanical load-to-failure for rotator cuff tendons augmented with BMS [21, 22]. The proposed biological mechanism behind BMS improving rotator cuff tendon healing is believed to be the release of local autogenous growth factors (e.g., PDGF-B, TGF-β1), which are implicated in true tendon healing [23]. Additionally, BMS allows for the release of bone marrow MSCs , which are implicated in paracrine signaling, promote angiogenesis and subsequently enthesis revascularization, and have anti-inflammatory effects [24].

Surgical technique for bone marrow stimulation

In the senior author's approach to RCR, diagnostic arthroscopy, potential subacromial decompression, management of the long head of the biceps tendon, and mobilization of the rotator cuff tendon to be repaired are performed in a standard fashion. Next, degenerative tissue at the tendon footprint is first debrided using a motorized shaver or burr. This is followed by careful arthroscopic decortication of calcified or sclerotic bone at the greater tuberosity footprint. The decortication is performed under direct visualization through a standard lateral portal while the arthroscopic shaver is inserted through the anterolateral portal. Microfracture is then performed using a curved microfracture awl or a specialized curved microfracture drill (◘ **Fig. 2a**), which offers the advantage of clearing debris from the perforation site compared with the traditional awl. Following the placement of medial-row anchors for the RCR, precise BMS via marrow venting is performed until the emergence of fatty marrow elements from the cancellous bone is observed. Microfracture holes are created at intervals of 3–4 mm, with a typical total of four to six perforations (◘ **Fig. 2b**). Drilling is performed to a depth of 5–10 mm to ensure adequate release of bone marrow elements, optimizing the biological environment for tendon-to-bone healing. The RCR is then completed with lateral-row fixation.

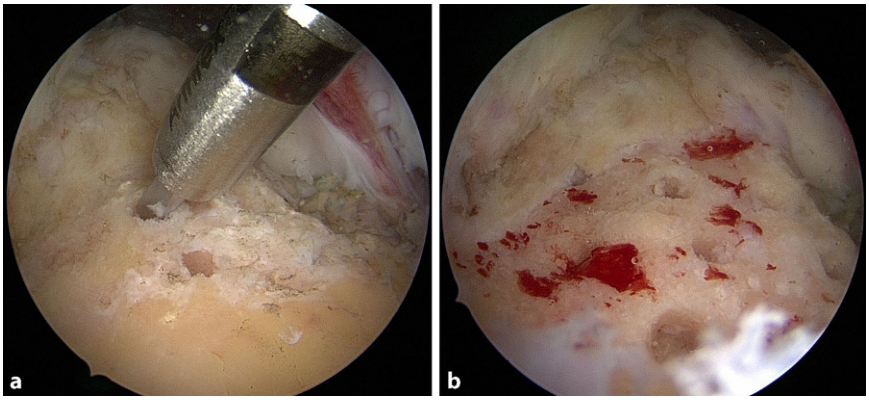

Fig. 2 ▲ Bone marrow stimulation: arthroscopic view of a left shoulder illustrating the bone marrow stimulation technique at the supraspinatus footprint. The procedure targets precise marrow venting regions on the bone surface using a curved microfracture drill (PowerPick, Arthrex, Naples, FL, USA; **a**), with perforations spaced 3–4 mm apart (**b**). These controlled microfractures stimulate the release of growth factors and mesenchymal stem cells from the bone marrow, enhancing the biological environment for tendon-to-bone healing in rotator cuff repair. (Courtesy of PD Dr. Bastian Scheiderer, MD)

Bone marrow aspirate concentrate

Biological principle

Augmentation with BMAC has emerged as a prominent biological augmentation strategy in the field of orthobiologics. The BMAC is harvested from the intramedullary canal of three well-known sites: the iliac crest, proximal tibia, or proximal humerus [25]. The efficacy of BMAC is believed to stem from its ability to manipulate and concentrate specific cellular, cytokine, and growth factor populations [26]. In addition, regenerative capacity is achieved, as MSCs are within the harvested population, thus facilitating the ability to differentiate into bone, cartilage, or tendons [9]. Furthermore, the anti-inflammatory properties are provided by the associated increasing concentration of interleukin 1 receptor antagonist (IL-1Ra) in the final concentrate [26]. Consequently, the pro-inflammatory and tissue-degrading effects of excessive inflammation are regulated and suppressed, promoting enhanced biological healing [26].

In recent years, BMAC has been theorized to enhance biological healing due to the ability of the MSC population to differentiate into mesenchymal-origin cells, including bone, tendon, muscle, and cartilage [9]. This differentiation increases the density of type I collagen fibers, resulting in a more mechanically stable repair construct and enhanced local biological healing that resembles the native enthesis morphology [9]. This has been demonstrated in preclinical models where BMAC-augmented rotator cuff animal models demonstrated improved outcomes in comparison with standard cuff repairs [14, 27].

Gulotta et al. [14] observed enhanced mechanical and histological properties—specifically load to failure, stiffness, and fibrocartilage density—in rat rotator cuff models injected with scleraxis-transduced bone marrow MSCs compared with those receiving only MSCs. Their results reflect the importance of additional cellular, cytokine, and growth factor manipulation, a key principle behind BMAC utilization. Similarly, in rabbit rotator cuff models, Liu et al. [27] demonstrated that BMAC-augmented repairs biomechanically and histologically outperformed those treated with normal saline (NS), PRP, and bone marrow aspirate (BMA) at 6 weeks post-surgery. They attributed the ability of BMAC to enhance biological healing to its higher concentrations of MSCs, regulation of the inflammatory cascade (via increased IL-1Ra), and the vast presence of associated growth factors such as VEGF, PDGF, TGF, and IGF, compared with NS, PRP, and BMA. However, translating these promising preclinical results into clinical practice requires further evaluation.

Surgical technique of bone marrow aspirate concentrate augmentation

While harvesting from the iliac crest is generally possible, the senior authors of this review prefer harvesting BMAC from the proximal humerus for RCR augmentation due to its proximity to the surgical site. This technique has been described in detail by Allahabadi et al. [25].

Before starting the concomitant surgical procedure, the osseous landmarks proximal humerus and glenohumeral joint are identified. The harvesting needle is positioned 3 cm distal to the midpoint between the anterior and posterior acromial borders and directed into the intramedullary cavity while aiming medially, anteriorly, and inferiorly (**Fig. 3a**). A sharp trocar located within the needle's inner circle aids in penetration of the humeral cortex to a depth of ~3 cm. A mallet is used to adequately position the needle within the cancellous bone, past the nearby bony cortex (**Fig. 3b**). Once the needle is properly placed, the inner trocar stylet is removed, leaving the needle in situ. Two anticoagulant 30-mL syringes are used sequentially to aspirate a total of 60 mL of bone marrow (**Fig. 3c**). Aspiration is facilitated by rotating the syringe 90° every 5–10 mL (**Fig. 3d**), thus enhancing trabecular breakdown and further content aspiration. After aspiration, the needle is withdrawn, and the specimen is taken for processing while the concomitant surgical procedure continues.

Processing of the specimen begins with filtering of the aspirate, i.e., by using the Angel system (Arthrex). This is followed by centrifugation at the 7% setting to isolate and concentrate the desired cellular, growth factor, and cytokine populations, yielding approximately 5 mL of BMAC. The supernatant is then placed in a sterile syringe and returned to the surgical field for application. First, watertight closure of all arthroscopic portals and removal of excess intra-articular fluid are performed before BMAC injection to prevent extravasation and dilution of the concentrate, respectively. The BMAC can then be applied to the RCR, with half of the BMAC volume injected into the tendon at the bone junction and the remaining half injected at the footprint site.

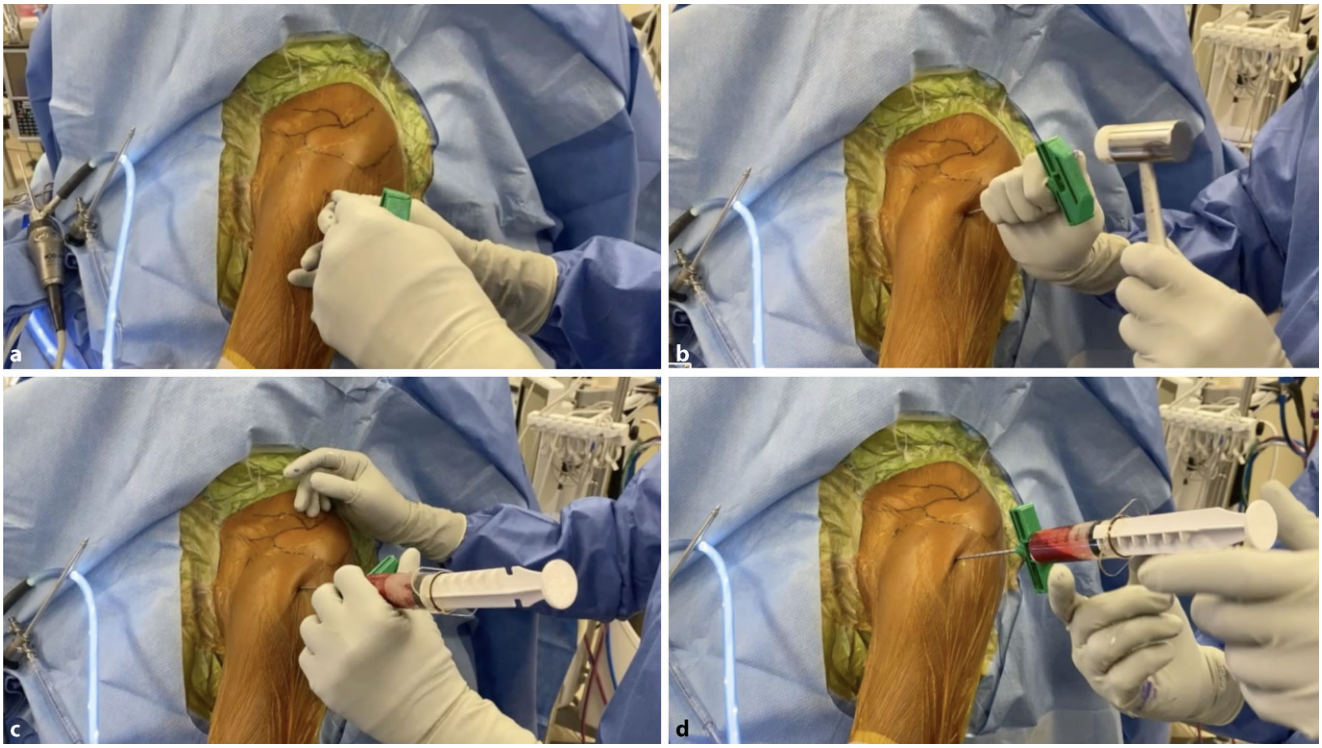

Fig. 3 ▲ Bone marrow aspirate harvesting: bone marrow aspiration performed from the proximal humerus. The harvesting needle (Arthrex, Naples, FL, USA) is inserted 3 cm distal to the midpoint between the acromial borders (**a**) and directed medially, anteriorly, and inferiorly. A mallet is used to impact the needle (**b**) and approximately 60 mL of bone marrow is aspirated (**c**) using slight twists (**d**) for further processing

By harvesting the sample at the beginning of the procedure, this technique allows the specimen to be processed concurrently with the RCR, thereby expediting the overall process. Additionally, the proximity of the proximal humerus eliminates the need for patient repositioning, further streamlining the harvesting process. However, this technique has its limitations. It requires specialized equipment and expertise to ensure a smooth BMAC harvest and processing. Furthermore, the quality of the BMAC harvest from the proximal humerus may be compromised in older individuals.

Clinical outcomes for bone marrow-based augmentation

Clinical outcomes for BMS have been mixed, with varying findings in large-scale clinical studies. A 2013 randomized clinical trial by Milano et al. randomized 80 patients to undergo arthroscopic RCR with and without BMS, finding no differences in tendon structural integrity during a minimum 2-year postoperative imaging follow-up [28]. However, the authors noted greater healing among patients receiving BMS for repairs involving both the supraspinatus and infraspinatus tendons. A 2023 randomized clinical trial by Shibata et al. had similar findings, with no differences in re-tear rates or patient-reported outcomes at a minimum 2-year follow-up among 60 patients undergoing arthroscopic knotless suture-bridge RCR [29]. A 2023 meta-analysis by Le Breton et al. reported promising outcomes, with significant improvements in re-tear rates and Constant scores for patients receiving BMS [30]. However, a 2024 meta-analysis of prospective, randomized clinical studies of BMC found no differences in healing rates, patient outcomes, range of motion, or complication rates [31]. The results of these studies demonstrate that the clinical efficacy of the technique may be limited. However, despite conflicting clinical evidence, BMS may represent a simple and cost-effective surgical adjunct to RCR.

Although preclinical data have suggested that BMAC augmentation enhances the mechanical and histological properties of repairs, only a few studies have investigated whether these findings translate to the clinical setting [32–34]. In a recent randomized controlled trial, Cole et al. [32] compared RCR outcomes in a cohort of small and medium tears (1–3 cm) augmented with BMAC versus a non-augmented cohort. Their findings indicated that, although BMAC-augmented repairs showed enhanced tendon integrity at the 1-year postoperative magnetic resonance imaging follow-up, as measured by the Sugaya score (57% vs. 18% re-tear rate, $p < 0.001$), clinical outcomes and failure rates were not significantly different between groups at the final 2-year follow-up (16% vs. 15% failure rate, $p > 0.05$). By contrast, Hernigou et al. [33] assessed the 10-year results of BMAC-augmented single-row RCR for small and medium-sized tears (1.5–2.5 cm). Their study found that the enhanced tendon integrity observed with BMAC augmentation translated into the clinical setting at the 10-year time point, with a significantly lower rate of clinical failures/re-tears in the BMAC-augmented group compared with the group

of non-augmented repairs (87% vs. 44%, $p < 0.05$). Additionally, Schoch et al. [34], while analyzing a national database, found that patients with BMAC-augmented RCR were significantly less likely to undergo revision surgery compared with those who had non-augmented repairs (odds ratio = 0.36, $p < 0.015$).

Studies with a high level of evidence are warranted to fully assess the potential of BMAC augmentation for RCR, particularly in the context of age-related decline in MSC potency and concentration, especially in older patients—who are often the target population for RCR. However, the limited literature available to date suggests that the observed enhancement of tendon healing with BMAC might translate into improved clinical outcomes, as demonstrated by both Hernigou et al. and Schoch et al. [33, 34].

Summary

Bone marrow-based augmentation techniques, specifically BMS and BMAC as biological adjuvants for RCR, have shown promise in enhancing RCR healing. Although clinical outcomes remain mixed, BMS has been noted for its low cost and low effort with reported effects on tendon-to-bone healing through the release of growth factors and MSCs. While BMS demonstrated superior outcomes in earlier meta-analyses, it did not consistently demonstrate superior outcomes in more recent literature syntheses. Bone marrow aspirate concentrate , with its concentrated MSC population, has demonstrated improved mechanical and histological properties in preclinical models. Augmentation with BMAC shows initial potential, with preclinical studies and early clinical evidence indicating superior tendon integrity and lower re-tear rates; however, results are not universally positive. The variability in outcomes underscores the need for further research to refine these techniques and better understand their role in different patient populations.

Implications for clinical practice

The application of BMS and BMAC should be considered selectively based on patient-specific factors such as age, tear size, and healing potential. While these techniques may offer potential benefits, particularly in biologically challenging cases, their use should be guided by current evidence and tailored to individual patient needs. Bone marrow stimulation offers a low-cost, low-effort option to mobilize bone-marrow-sized MSCs, and there are limited adverse effects. Currently, BMAC augmentation is predominantly available in specialized centers, limiting its widespread adoption. To establish this technique as a standard option for a broader patient population, further clinical research is essential, particularly to better understand its long-term efficacy across diverse patient groups. Additionally, addressing the geographic and insurance-related variability in reimbursement policies is critical.

In terms of future perspectives, the field of biological augmentation in RCR is still young, and there remains potential for significant advancements. In the future, advances in scaffold technologies may present additional advantages by offering more robust support at the repair site via integration into the tendon. Furthermore, combination therapies that combine BMAC or BMS with other biological augments, such as PRP, may present a promising avenue for improving healing outcomes by leveraging the synergistic effects of different types of concentrates [35]. While early results are encouraging, there is a clear need for further clinical studies to enhance patient selection, validate these augmentation approaches, and establish standardized preparation and application protocols to ultimately deliver a solid scientific ground for a reliable improvement of patient outcomes.

Practical conclusion

- **For optimal outcomes in rotator cuff repair (RCR), shoulder surgeons can integrate biological augmentation techniques based on patient-specific factors.**
- **Bone marrow stimulation offers a straightforward and cost-effective method to enhance tendon-to-bone healing by releasing growth factors and stem cells directly at the repair site.**
- **Bone marrow aspirate concentrate is a more advanced biological augmentation option that can concentrate and deliver a high population of mesenchymal stem cells, along with anti-inflammatory cytokines, thereby potentially improving tendon integrity and reducing re-tear rates.**
- **To effectively incorporate these techniques into clinical practice, the patient's biological status in terms of age, tear size, chronicity, and overall healing potential should be evaluated.**
- **As new data emerge, it is crucial to refine patient selection criteria and surgical protocols to maximize the benefits of these augmentation strategies on the way to personalized RCR strategies.**

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Declarations

Conflict of interest. M.-C. Rupp: *Arthroscopy* journal: Editorial Board Member, AGA Society for Arthroscopy: Committee member. N. Verma discloses the following: American Orthopaedic Society for Sports Medicine: Board or committee member; American Shoulder and Elbow Surgeons: Board or committee member; Arthrex, Inc: IP royalties; Research support; Arthroscopy Association of North America: Board or committee member; Breg: Research support; Ossur: Research support; SLACK Incorporated: Editorial or governing board; Smith & Nephew: IP royalties; Research support; Stryker: IP royalties; Paid consultant; Research support. J. Chahla reports a relationship with the American Orthopaedic Society for Sports Medicine: Board or committee member; Arthrex, Inc: Paid consultant; Arthroscopy Association of North America: Board or committee member; CONMED Linvatec: Paid consultant; International Society of Arthroscopy, Knee Surgery, and Orthopaedic Sports Medicine: Board or committee member; Ossur: Paid consultant; Smith & Nephew: Paid consultant; Paid presenter or speaker. J. Villarreal and Z.A. Khan declare that they have no competing interests.

For this article no studies with human participants or animals were performed by any of the authors. All

studies mentioned were in accordance with the ethical standards indicated in each case.

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Zusammenfassung

Knochenmarkbasierte Augmentation in der Rotatorenmanschettenrekonstruktion – von Mikrofrakturierung bis Knochenmarkaspirat

Rotatorenmanschettenrupturen gehören zu den häufigsten pathologischen Veränderungen der Schulter, und trotz chirurgischer Fortschritte bleiben die Rerupturraten insbesondere bei Patienten mit eingeschränktem biologischem Heilungspotenzial relativ hoch. Um die biologische Umgebung an der Reparaturstelle zu optimieren und dadurch möglicherweise die Ergebnisse zu verbessern, wurden knochenmarkbasierte Augmentationstechniken eingeführt, insbesondere die Mikrofrakturierung am Sehnenfootprint und die Applikation von konzentriertem Knochenmarkaspirat (BMAC). Die Knochenmarkstimulation, die häufig durch Mikrofrakturierung erreicht wird, fördert die Freisetzung von Wachstumsfaktoren und mesenchymalen Stammzellen aus dem Knochenmark, was die Integration der Sehne in den Knochen begünstigen soll. Trotz ihrer Einfachheit und Kosteneffizienz sind die klinischen Ergebnisse der Mikrofrakturierung uneinheitlich; aktuellste Metaanalysen zeigen keine signifikante klinische Überlegenheit in Bezug auf die relevanten Ergebnisse im Vergleich zu konventioneller Rotatorenmanschettenrekonstruktion. Die BMAC-Augmentation stellt einen differenzierteren Ansatz dar, indem mesenchymale Stammzellen und entzündungshemmende Zytokine konzentriert werden, um den Heilungsprozess direkt zu unterstützen. Präklinische Studien haben gezeigt, dass BMAC zu einer verbesserten Sehnenintegrität und biomechanischen Festigkeit führen kann. Spärlich vorhandene klinische Studien deuten darauf hin, dass BMAC die Rerupturraten senken und die Sehnenheilung fördern könnte, wenngleich die Ergebnisse bislang nicht durchweg optimal sind. Die aktuelle Evidenz unterstreicht das Potenzial dieser Techniken, insbesondere in Fällen mit schwierigen biologischen Ausgangsbedingungen. Allerdings zeigt die Variabilität der klinischen Ergebnisse den Bedarf an weiterführender Forschung, um diese Methoden zu verfeinern und ihre Anwendung in der klinischen Routine zu etablieren.

Schlüsselwörter
Knochenmarkstimulation · Biologische Augmentation · Orthobiologika · Mesenchymale Stammzellen · Schulter

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