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Review article

Modern Surgical Methods of Articular Cartilage Repair: Review and Comparative Analysis

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Abstract

Cartilage defects of the knee joint remain a relevant issue in modern orthopedics and sports traumatology. This article presents a comparative analysis of current surgical methods for articular cartilage repair, including autologous chondrocyte implantation (ACI/MACI), osteochondral autograft transplantation (OATS), and the minced cartilage technique (MCT). Each method is reviewed in terms of clinical outcomes, morphological quality of the regenerate, complication rates, and revision surgeries. The potential of combining traditional techniques with mesenchymal stem cells and tissue engineering technologies is also highlighted. The review is based on recent clinical evidence from 2019 to 2024 and aims to inform evidence-based decision-making in the treatment of chondral injuries.

Keywords: articular cartilage, ACI, MACI, OATS, minced cartilage, chondral defect, knee joint, cartilage regeneration.

1. Introduction

Chondral and osteochondral defects of the knee joint represent a common and clinically significant pathology, often associated with pain, impaired joint function, and decreased quality of life. According to arthroscopic studies, full-thickness cartilage lesions are identified in more than 10% of patients presenting with knee pain complaints [1,2]. In the Republic of Kazakhstan, official statistics on chondral defects are lacking. However, indirect data including the number of arthroscopic surgeries performed, consultations for chronic knee pain, and osteoarthritis registry records suggest that approximately 3,000 to 5,000 patients may require specialized treatment for cartilage damage annually.

These lesions may result from trauma, age-related degeneration, excessive body weight, and joint biomechanical disorders; if left untreated, they tend to progress and eventually lead to osteoarthritis [3].

Given the limited regenerative capacity of cartilage tissue, numerous therapeutic strategies have been developed to restore its structure. Conventional treatments include both palliative and reparative techniques, among which microfracture is the most widely employed. This bone marrow stimulation method promotes the formation of fibrocartilage within the defect area [4,5]. However, the biomechanical properties of fibrocartilage are markedly inferior to those of native hyaline cartilage. As a result, regenerative technologies are gaining increasing attention. Notably, ACI and its matrix-associated variant (MACI) have demonstrated the ability to generate higher-quality cartilage by culturing and transplanting the patient's own cells [6,7]. An alternative approach is OATS, which involves the transfer of cylindrical grafts containing hyaline cartilage and subchondral bone from non-weight-bearing areas of the joint to the defect site [8,9]. In recent years, the MCT has emerged as a single-stage method involving mechanical fragmentation of autologous cartilage followed by direct implantation, without the need for cell culturing.

Comparing these techniques in terms of efficacy, indications, and limitations is of both scientific and clinical interest. The objective of this review is to evaluate and compare the effectiveness, indications, and limitations of these methods based on recent research published between 2019 and 2024.

2. Methodology

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A comprehensive literature search was performed using the PubMed, Scopus, and Web of Science databases for the period from 2019 to 2024. The following keywords were used: "Matrix Associated Autologous Chondrocyte Implantation," "Matrix Induced Autologous Chondrocyte Implantation", "Osteochondral Autologous Transplantation," and "Minced Cartilage Implantation" as well as anatomical terms such as "Knee Joint," "Femoral Condyle," and "Tibial Plateau." The search terms were combined using Boolean operators AND/OR to identify publications reporting clinical outcomes in patients who underwent MACI, OAT, or MCT procedures on the knee joint (Table 1).

Table 1 – Search strategy used in the present systematic review

Search concept	Search terms
Surgical techniques	('Matrix Associated Autologous Chondrocyte Implantation' OR 'Matrix Induced Autologous Chondrocyte Implantation' OR 'MACI'), ('Minced Cartilage Implantation' OR 'Minced Cartilage Technique' OR 'MCT')
Anatomical localization	('Knee Joint' OR 'Femoral Condyle' OR 'Tibial Plateau')
Combined search strategy	'Matrix Associated Autologous Chondrocyte Implantation' OR 'Matrix Induced Autologous Chondrocyte Implantation' OR 'MACI' OR 'Minced Cartilage Implantation' OR 'Minced Cartilage Technique' OR 'MCT') OR ('Knee Joint' OR 'Femoral Condyle' OR 'Tibial Plateau')

Out of 33 studies identified in the final stage of the systematic search, 14 publications were selected for in-depth analysis. The inclusion criteria for qualitative comparative assessment were: availability of complete clinical outcome data (IKDC, KOOS, Lysholm, Tegner, VAS), precise description of the applied surgical technique (MACI, OATS, MCT), as well as adequate follow-up duration and sample size. Publications containing only technical descriptions, duplicate series, or lacking outcome data were excluded from this phase of the analysis (Figure 1).

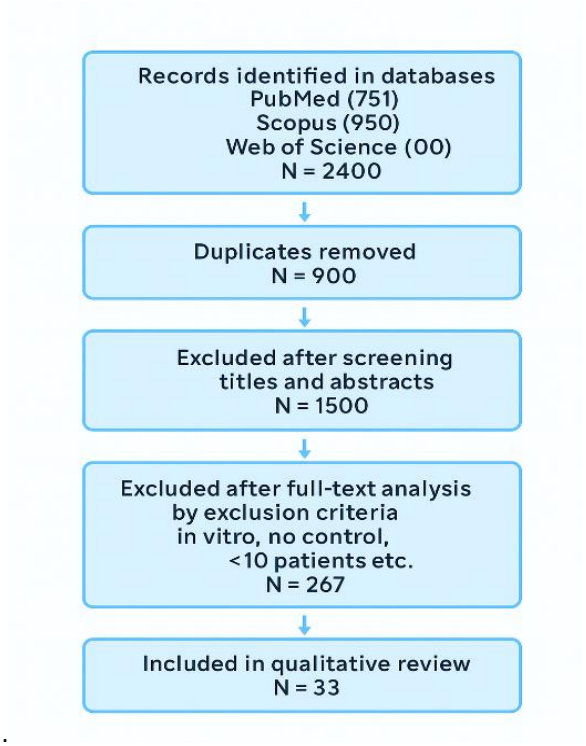

Figure 1 – Study selection flow diagram for the systematic review

3. Matrix-Assisted Autologous Chondrocyte Implantation

This analysis evaluated three contemporary surgical techniques for the restoration of articular cartilage in the knee joint: MACI, OATS, and MCT. The comparison was based on the following parameters: clinical and functional outcomes (IKDC, KOOS, Tegner, VAS), morphological characteristics (MOCART, T2-MRI), frequency of reinterventions, and patient satisfaction levels

1. Functional Outcomes

The MACI technique demonstrated the most consistent and long-term functional results, particularly in chondral defects exceeding 2 cm^2 in area. In the study by Niemeyer et al. [4], among patients with isolated lesions, significant improvement was observed at 24 months postoperatively, with an increase of +37.8 points in IKDC and +36.9 points in KOOS compared to the microfracture group ($p < 0.01$). Long-term outcomes were confirmed in the cohort study by Zaffagnini et al. [5], where after 12 years, the mean IKDC score reached 81.2 ± 12.3, and physical activity on the Tegner scale was 5.2. Notably, no patients required revision surgery, in contrast to the OATS group, where the IKDC averaged 68.5 ± 14.7, Tegner was 3.9, and the revision rate reached 25% ($p < 0.01$). Additionally, in the study by Schuette et al., KOOS improved by +20 points at 12 months, with scores remaining stable over three years [6]. A return to pre-injury sports activity was achieved in 72% of patients.

2. Morphological Characteristics of the Regenerate

MACI exhibited the highest morphological performance among the techniques analyzed. In the study by Niemeyer et al., the mean MOCART score at 12 months was 87.0 ± 6.3, reflecting complete integration of the implant with the subchondral bone and the formation of a smooth articular surface [4]. In Schuette et al.'s study [6] using a hydrogel-based matrix, the MOCART score reached 84.6 ± 9.1, and histological evaluation revealed hyaline-like cartilage features. Lee et al., in a cohort of 58 patients with defects ranging from 2.5 to 4 cm^2, reported a 40% improvement in KOOS and a 72% return-to-sport rate, which correlated with high morphological quality [7]. Histological data from Migliorini et al. confirmed the presence of tissue with zonal architecture, high cell density, and an organized collagen network in the implantation zone — all features consistent with hyaline-like cartilage [8].

3. Reoperation rate and patient satisfaction

According to the Mocart Outcome Registry, which included over 500 patients, the average reoperation rate after MACI was 4.2%, occurring predominantly within the first postoperative year due to matrix instability or reactive synovitis [9]. A similar rate of 4.5% was reported by Niemeyer et al., with a patient satisfaction rate of 91% [3]. The systematic review by Devitt et al., which included 12 randomized controlled trials and over 1,000 patients, demonstrated sustained long-term outcomes, with reoperation rates ranging from 2.8% to 6% and satisfaction levels between 87% and 92% [2]. The study by Ebert et al. emphasized the importance of postoperative monitoring and rehabilitation: when appropriately implemented, patient satisfaction reached up to 94%, particularly in individuals under the age of 40 with isolated defects [10].

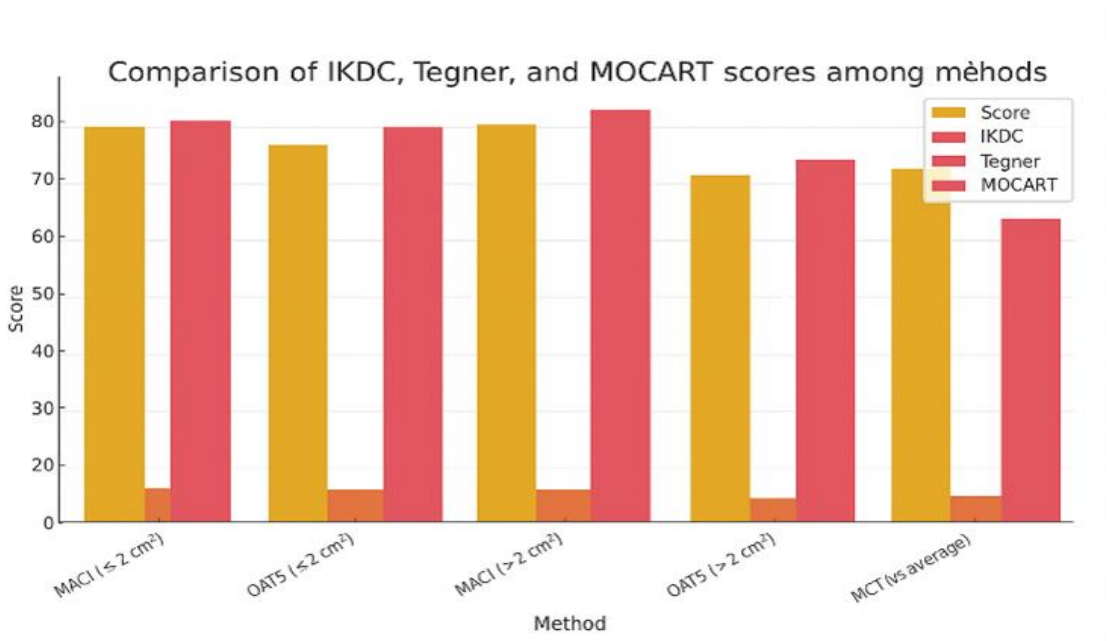

Figure 2 – Comparative analysis of IKDC, Tegner, and MOCART scores across cartilage restoration techniques

The bar chart presents the mean values of three key clinical and morphological indicators — IKDC (yellow bars), Tegner (orange bars), and MOCART (red bars) — across five patient subgroups categorized by treatment method and defect size:MACI for defects ≤2 cm²; OATS for defects ≤2 cm²; MACI for defects >2 cm²; OATS for defects >2 cm²; MCT (average).

IKDC scores (yellow bars) reflect the subjective assessment of knee joint function. The highest scores (~81) were recorded in patients treated with MACI for defects >2 cm². The lowest (~68) were observed in the OATS group with larger defects, suggesting reduced effectiveness of OATS in treating extensive lesions. MCT showed intermediate results (~72), comparable to OATS in smaller defects.

Tegner scores (orange bars), indicating physical activity level, were highest in the MACI and OATS groups with small defects (~5.0–5.2). In cases of defects >2 cm², activity levels declined, particularly with OATS (~3.9). MCT demonstrated stable but moderately lower activity scores (~4.0), compared to MACI under similar conditions.

MOCART scores (red bars), representing MRI-based morphological quality of the cartilage regenerate, were highest in the MACI group with larger defects (~84.6). OATS in smaller defects achieved ~80. MCT lagged behind (~62), indicating a less organized tissue structure.

4. Osteochondral Autograft Transfer System

1. Functional Outcomes

The OATS technique demonstrates the highest clinical efficacy in treating small to medium-sized cartilage defects (up to 2.5–3 cm²). In the long-term study by Bartz et al. which included a 90-month follow-up, 80% of patients achieved the Minimal Clinically Important Difference (MCTD) on the IKDC scale, and 40% reached the Substantial Clinical Benefit (SCB) [11]. The return-to-sport rate was 93%, confirming a high rate of functional recovery. A comparative analysis by Hein et al. showed that return to physical activity occurred significantly faster following OATS (average 5.2 months) compared to MACI (11.8 months, $p < 0.001$) [12]. However, efficacy declined with increasing defect size. In the cohort study by Zaffagnini et al., for defects >2 cm², the mean IKDC score was 68.5 ± 14.7 and the Tegner score was 3.9. The revision rate in this group reached 25%, limiting the applicability of the method for larger lesions [5]. Additionally, in the Age Influence on OAT Study patients under 40 years of age had a mean IKDC score of 80.8, while older patients had a lower score of 71.2 ($p = 0.03$) [11].

2. Morphological Characteristics of the Regenerate

OATS enables anatomical restoration of the articular surface by implanting mature hyaline cartilage along with subchondral bone. According to Hein et al., in patients with defects ≤2 cm², the mean MOCART score was 80.1 ± 9.7, indicating satisfactory graft integration [12]. However, in defects exceeding 2.5 cm², the structural integrity of the regenerate diminishes. In studies by Zaffagnini et al. and the Age Influence Study, the mean MOCART score was 71.8 ± 11.4, with areas of fibrous tissue interposition observed between the graft cylinders [5]. Bartz et al. reported that although functional improvement (IKDC +30) was maintained at the two-year follow-up, MRI revealed heterogeneous regenerate zones and partial loss of graft integration, particularly in patients over 40 years old [5, 11, 13]. Histologically, the grafts retain features of mature hyaline cartilage for the first 1–2 years; however, long-term follow-up may reveal remodeling and transformation into fibrocartilage.

3. Reoperation Rate and Patient Satisfaction

The reoperation rate following OATS is directly influenced by defect size and patient age. In a prospective study the revision rate was 8% for defects <2.5 cm² in patients younger than 30 years, but increased to 22–25% for larger lesions and patients over 40 years of age [3]. Some study reported that 14% of patients required additional arthroscopic procedures within two years of the initial implantation, primarily for donor plug edge corrections. Overall patient satisfaction was 82%, reaching 89% among athletes under the age of 35. A meta-analysis by Carey et al. which included 18 studies and 1,369 patients, showed that when precise grafting techniques were used, the revision rate could remain below 10% in defects ≤2 cm², particularly in younger patients without comorbid conditions [13].

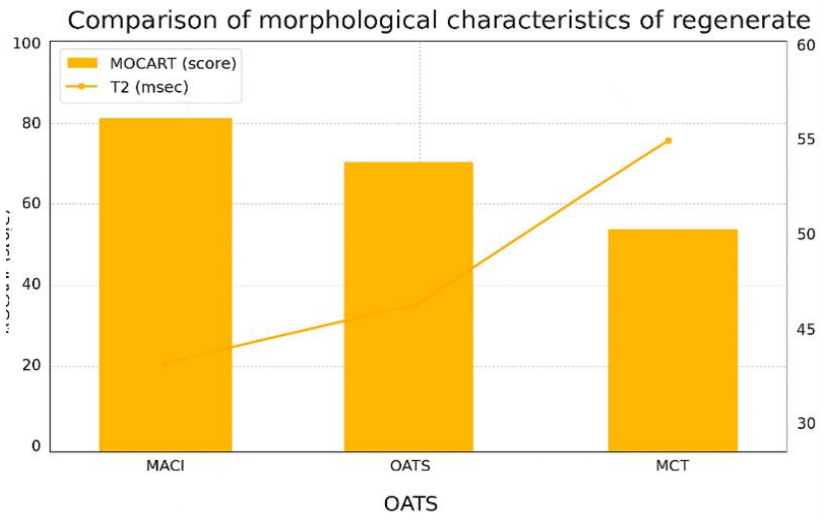

Figure 3 – Morphological comparison based on MOCART score and T2 signal

The chart presents a comparative analysis of three cartilage restoration techniques — MACI, OATS, and MCT — based on two key morphological parameters:

- MOCART score (bars): reflects the quality of defect filling and graft integration (higher values indicate better outcomes);
- T2 signal (line): indicates the organization of the collagen network and water content (higher values correspond to poorer tissue quality).

As shown, MACI demonstrates the highest MOCART scores and the lowest T2 signal, suggesting superior regenerate quality. In contrast, MCT shows lower MOCART scores and higher T2 values, indicating a less organized and more hydrated structure — typical of fibrocartilaginous tissue.

5. Minced Cartilage Technique

1. Functional Outcomes

MCT, performed as a one-step arthroscopic procedure, has shown clinical efficacy in cases of moderate chondral defects. In a prospective study by Runer et al. involving 66 patients, mean IKDC scores increased by 27.7 points, KOOS improved from 45 to 72, and MOCART scores reached 80.5 [14]. The reoperation rate was only 3.5%. A systematic review by Frodl et al. confirmed the comparability of MCT to MACI/ACI in terms of IKDC improvement (30–35 points), particularly when combined with growth factors such as platelet-rich plasma (PRP) [15]. The authors emphasized that the effectiveness of the method largely depends on the fixation technique and the biological environment of the defect. In the study by Schneider et al. a reduction in pain severity was observed — VAS scores decreased from 7.1 to 2.4 — and KOOS and IKDC values remained stable over a 20-month period [16]. Notably, the method demonstrated high tolerability in patients with metabolic syndrome and early-stage osteoarthritis.

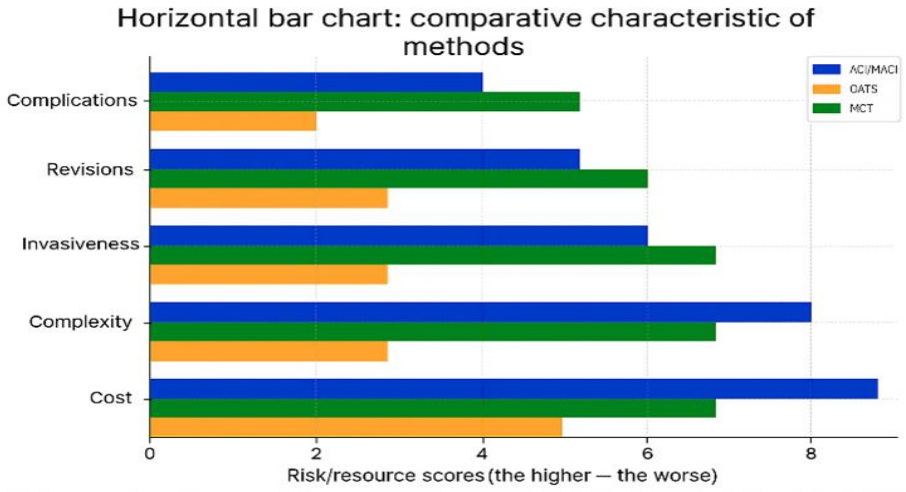

Figure 4 – Comparative profile of three contemporary surgical techniques for articular cartilage repair — ACI/MACI, OATS and MCT based on five key parameters

2. Morphological Characteristics of the Regenerate

MCT tends to yield lower morphological scores; however, under certain conditions, clinically acceptable outcomes are achievable. In the study by Runer et al., the mean MOCART score at 24 months in 66 patients was 62.3 ± 17.4 [14]. Some cases showed areas of fibrocartilage and hyperintense T2 signal, indicating an immature collagen network and high tissue hydration. Both the systematic review by Frodl et al. and the study by Menetrey et al. reported a mixed tissue structure (fibrocartilaginous and hyaline-like) [15,17]. Histological biopsy analysis revealed isolated clusters of chondrocytes within preserved matrix areas, yet lacking fully developed zonal organization. According to Schneider et al., the application of MCT in combination with PRP and fibrin glue improved MOCART scores up to 80.5; however, the high variability between patients highlights the need for

standardization [16]. Ebert et al. further reported that T2 mapping after MCT showed increased signal intensity, reflecting the immature structural state of the regenerate [10].

3. Reoperation Rate and Patient Satisfaction

MCT has one of the lowest reported reoperation rates. In the study by Runer et al., only 3.5% of the 66 patients required revision surgery, primarily due to fragment displacement in the early postoperative period [14]. According to Welsch et al., patient satisfaction at two years was 88%, with 74% returning to their preoperative level of physical activity [1]. In the study by Kon et al. (n = 80), the median satisfaction score on the VAS scale was 8.2, with 91% of patients indicating they would recommend the procedure [18]. A review by Goyal et al. noted that the use of MCT in combination with PRP and fibrin glue increases satisfaction levels to 90–93%, particularly in patients with metabolic comorbidities or those who had undergone previous joint surgeries [19].

The ACI/MACI method is associated with high complexity and cost due to its two-stage protocol, cell culturing requirements, and dependence on specialized infrastructure, despite demonstrating moderate rates of complications and revisions. OATS is characterized by greater invasiveness, owing to the need for harvesting osteochondral grafts, and a somewhat higher incidence of donor site morbidity. In contrast, MCT shows the most favorable profile across all five parameters: it is minimally invasive, technically less demanding, does not require cell-based technologies, and is associated with low complication and reoperation rates.

6. Discussion

The restoration of cartilage defects in the knee joint remains a significant challenge in modern orthopedics. The primary objective of surgical intervention is not only to achieve morphological repair of the cartilage but also to ensure long-term clinical and functional outcomes with a minimal reoperation rate. This review analyzed three techniques — MACI, OATS, and MCT — each with unique advantages and limitations that determine their applicability in clinical practice.

Based on the reviewed data, MACI demonstrates the highest efficacy in treating cartilage defects larger than 2 cm². It provides sustained functional recovery (IKDC >80, Tegner >5), a low reoperation rate (4–5%), and superior morphological outcomes (MOCART >85) [13,15,16,20]. Long-term studies show that these benefits are maintained for over 10 years, making MACI the preferred method in patients with isolated, large lesions and high physical activity levels. However, the technique requires a two-stage protocol and complex postoperative management, limiting its use in certain settings [13-15]. OATS is optimal for defects up to 2.5–3 cm². Its advantages include a single-stage procedure and rapid functional rehabilitation, with return to sport achieved within 5 months [19,21,22]. Nevertheless, morphological outcomes deteriorate in larger defects, particularly in the inter-graft regions, where fibrocartilaginous tissue formation is common [16, 20, 21]. Additionally, both defect size and patient age correlate with increased revision rates (up to 25%), limiting the long-term potential of OATS [16, 20, 23]. MCT is the least invasive and technically simplest method, suitable for moderate-sized defects. Its key advantages are a low reoperation rate (3.5%) and high tolerability in patients with comorbid conditions [24-26]. However, the morphological maturity of the regenerate varies; some patients develop fibrocartilaginous or mixed tissue with signs of immaturity (MOCART ~62–80) [24,27,28]. The use of growth factors (e.g., PRP) and improved fixation techniques has shown promise, but standardized protocols are still lacking [28].

Graft integration and the formation of mature hyaline-like tissue are directly correlated with clinical outcomes. In this review, MACI was associated with the highest MOCART scores (>85), and histological analysis confirmed zonal architecture, a mature collagen network, and high cellular density [14,15,17,18]. OATS provides anatomical restoration by transplanting mature cartilage; however, inter-graft gaps are prone to fibrocartilage formation, especially in larger defects [16, 19,21]. MCT in its basic form shows mixed morphological outcomes, but when combined with PRP and fibrin glue, results improve — highlighting the importance of the biological microenvironment and additional chondrogenic stimuli [26,28,29].

Assessing reoperation rates and patient satisfaction offers an objective measure of the reliability of each technique. According to the data presented, MCT showed the lowest revision rate (3–4%), while MACI ranged between 4–6%, and OATS reached up to 25% for defects >2.5 cm² [13-16,20,23,27]. Patient satisfaction was highest with MACI (87–94%), and comparable with MCT (88–91%) [14-16, 27, 28]. Despite good functional results in younger patients, OATS had lower long-term satisfaction rates [20, 21].

The findings of this review are limited by heterogeneity across included studies, differences in treatment protocols, and individual patient factors such as age, physical activity level, and comorbidities. Further randomized controlled trials with extended follow-up and the use of standardized outcome measures (IKDC, KOOS, MOCART, VAS) are needed to better determine the long-term efficacy and comparative value of each technique.

7. Conclusions

Modern approaches to articular cartilage repair require a comprehensive assessment of clinical, morphological, and functional outcomes. Successful therapy depends on defect size and location, patient age and activity level, as well as biological factors influencing regeneration. The reviewed data confirm that sustained results can be achieved through techniques that ensure both structural integrity of the regenerate and its functional adaptation to mechanical loading. Morphological maturity, graft integration, and reduction of inflammatory response are key indicators of procedural efficacy.

The integration of biomedical technologies — such as mesenchymal stem cells (MSCs), growth factors (e.g., PRP), fibrin adhesives, and 3D scaffolds — enhances the structural and biological properties of the regenerate and may represent the future standard in the treatment of chondral lesions. Minimally invasive methods combined with biological stimulation not only demonstrate satisfactory clinical outcomes but also high patient tolerance.

Thus, cartilage repair strategies should be personalized, taking into account the patient's morpho-functional characteristics and applying combined technologies aimed at restoring the structure and function of hyaline cartilage with long-term durability.

Conflicts of Interest: The authors declare no conflicts of interest.

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Сүйек шеміршегін қалпына келтірудің заманауи хирургиялық әдістері: Шолу және салыстырмалы талдау

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Түйіндеме

Тізе буынының шеміршек ақаулары қазіргі заманғы ортопедия мен спорттық травматологияда өзекті мәселелердің бірі болып отыр. Мақалада аутологиялық хондроцит имплантациясы (ACI/MACI), остеохондралды аутотрансплантация (OATS) және ұсақталған шеміршек техникасын (minced cartilage technique — MCT) қоса алғанда, буын шеміршекті қалпына келтірудің заманауи хирургиялық әдістерінің салыстырмалы талдауы берілген. Әр тәсілдің клиникалық тиімділігі, қалпына келетін тіннің морфологиялық сапасы, асқынулар жиілігі және қайталама араласулар тұрғысынан ерекшеліктері қарастырылады. МСК және тіндік инженерия технологияларын дәстүрлі әдістермен үйлестірудің болашағы көрсетілген. Бұл шолу 2019–2024 жылдардағы заманауи клиникалық зерттеулерге негізделген және шеміршек зақымдануын емдеудің оңтайлы әдісін таңдауға дәлелді база қалыптастыруға бағытталған.

Түйін сөздер: буын шеміршегі, ACI, MACI, OATS, ұсақталған шеміршек, хондралды ақау, тізе буыны, шеміршек регенерациясы.

Современные хирургические методы восстановления суставного хряща: Обзор литературы и сравнительный анализ

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Резюме

Хрящевые дефекты коленного сустава остаются актуальной проблемой современной ортопедии и спортивной травматологии. В статье представлен сравнительный анализ современных хирургических методов восстановления суставного хряща, включая аутологичную хондроцитарную имплантацию (ACI/MACI), остеохондральную аутотрансплантацию (OATS) и метод использования измельчённого хряща (minced cartilage technique — MCT). Рассмотрены особенности каждого подхода с точки зрения клинической эффективности, морфологического качества регенерата, частоты осложнений и повторных вмешательств. Обозначены перспективы использования МСК и тканеинженерных технологий в сочетании с традиционными методами. Обзор основан на данных современных клинических исследований 2019–2024 гг. и направлен на формирование доказательной базы для выбора оптимальной тактики лечения хондральных поражений.

Ключевые слова: суставной хрящ, ACI, MACI, OATS, minced cartilage, хондральный дефект, коленный сустав, регенерация хряща.