

# The American Journal of Sports Medicine

<http://ajs.sagepub.com/>

---

## **Clinical Efficacy of the Microfracture Technique for Articular Cartilage Repair in the Knee**

Kai Mithoefer, Timothy McAdams, Riley J. Williams, Peter C. Kreuz and Bert R. Mandelbaum

*Am J Sports Med* 2009 37: 2053 originally published online February 26, 2009

DOI: 10.1177/0363546508328414

The online version of this article can be found at:

<http://ajs.sagepub.com/content/37/10/2053>

---

Published by:



<http://www.sagepublications.com>

On behalf of:



[American Orthopaedic Society for Sports Medicine](#)

**Additional services and information for *The American Journal of Sports Medicine* can be found at:**

**Email Alerts:** <http://ajs.sagepub.com/cgi/alerts>

**Subscriptions:** <http://ajs.sagepub.com/subscriptions>

**Reprints:** <http://www.sagepub.com/journalsReprints.nav>

**Permissions:** <http://www.sagepub.com/journalsPermissions.nav>

# Clinical Efficacy of the Microfracture Technique for Articular Cartilage Repair in the Knee

## An Evidence-Based Systematic Analysis

Kai Mithoefer,<sup>\*†</sup> MD, Timothy McAdams,<sup>‡</sup> MD, Riley J. Williams,<sup>§</sup> MD, Peter C. Kreuz,<sup>||</sup> MD, and Bert R. Mandelbaum,<sup>||</sup> MD

From <sup>†</sup>Harvard Vanguard Orthopedics and Sports Medicine, Brigham and Women's/Faulkner Hospital, Harvard Medical School, Boston, Massachusetts, the <sup>‡</sup>Department of Orthopaedic Surgery, Stanford University Medical Center, Stanford, California, <sup>§</sup>Shoulder and Sports Medicine Service, Hospital for Special Surgery, New York, New York, the <sup>||</sup>Department of Orthopaedics, University of Freiburg, Freiburg, Germany, and <sup>||</sup>Santa Monica Orthopaedic and Sports Medicine Foundation, Santa Monica, California

**Background:** Despite the popularity of microfracture as a first-line treatment for articular cartilage defects in the knee, systematic information on its clinical efficacy for articular cartilage repair and long-term improvement of knee function is not available.

**Hypothesis:** Systematic analysis of the existing clinical literature of microfracture in the knee can improve the understanding of the advantages and limitations of this cartilage repair technique and can help to optimize its indications and clinical outcomes.

**Study Design:** Systematic review.

**Methods:** A comprehensive literature search was performed using established search engines (MEDLINE, EMBASE, CINAHL, Cochrane Central Register of Controlled Trials) to identify original human studies of articular cartilage repair with microfracture. Modified Coleman Methodology Scores were used to analyze the quality of the existing studies. Clinical efficacy of articular cartilage repair was evaluated by systematic analysis of short- and long-term functional outcome scores, macroscopic and microscopic repair cartilage quality, and findings of postoperative magnetic resonance imaging.

**Results:** Twenty-eight studies describing 3122 patients were included in the review. The average follow-up was 41 months, with only 5 studies reporting follow-up of 5 years or more. Six studies were randomized controlled trials and the mean Coleman Methodology Score was 58 (range, 22-97). Microfracture effectively improved knee function in all studies during the first 24 months after microfracture, but the reports on durability of the initial functional improvement were conflicting. Several factors were identified that affected clinical outcome. Defect fill on magnetic resonance imaging was highly variable and correlated with functional outcome. Macroscopic repair cartilage quality positively affected long-term failure rate, while the influence of histologic repair tissue quality remained inconclusive.

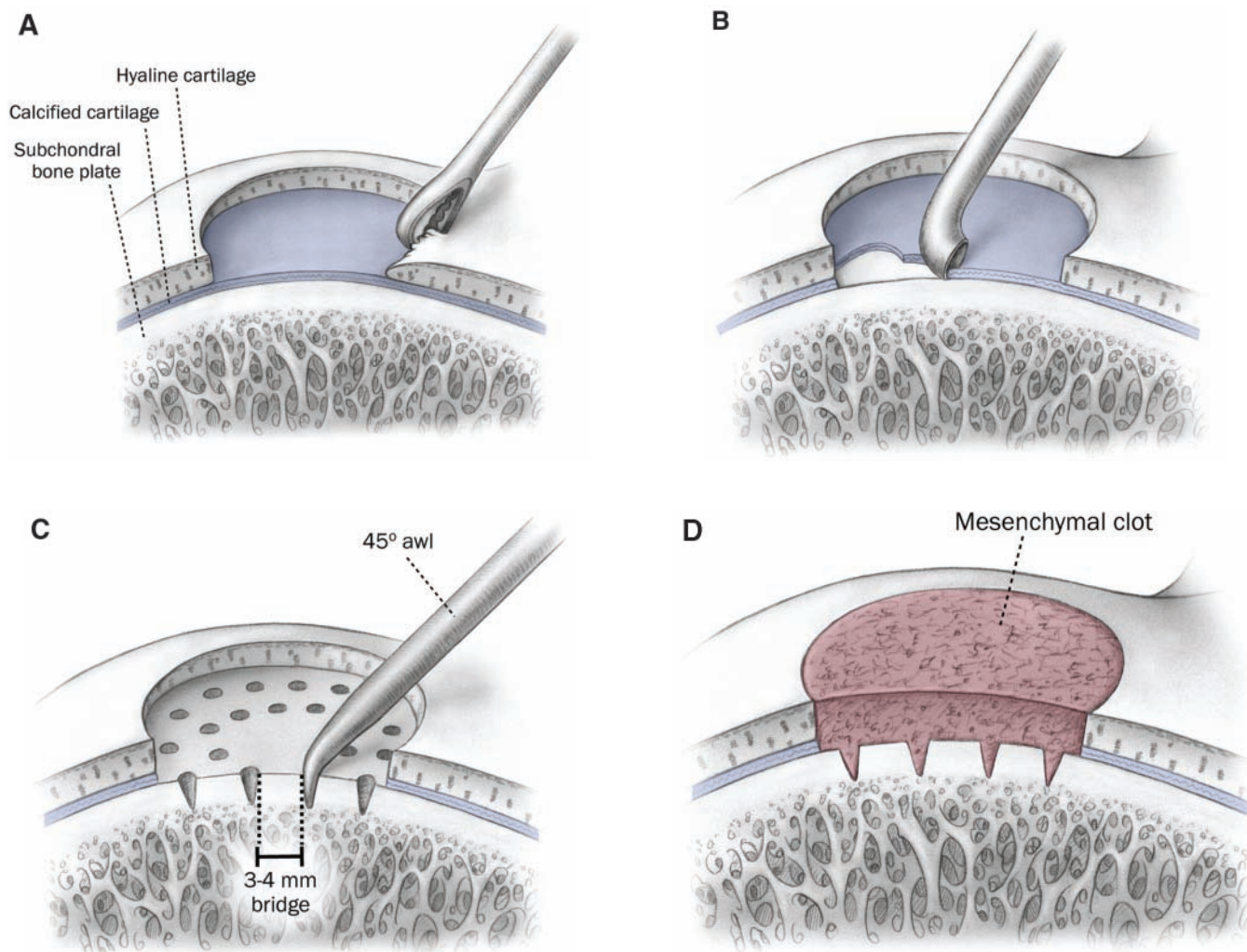
**Conclusion:** This systematic analysis shows that microfracture provides effective short-term functional improvement of knee function but insufficient data are available on its long-term results. Shortcomings of the technique include limited hyaline repair tissue, variable repair cartilage volume, and possible functional deterioration. The quality of the currently available data on microfracture is still limited by the variability of results and study designs. Further well-designed studies are needed to determine the long-term efficacy of microfracture and to define its specific clinical indications compared to other cartilage repair techniques.

**Keywords:** microfracture; cartilage; injury; repair; resurfacing; chondroplasty; knee

\*Address correspondence to Kai Mithoefer, MD, Harvard Vanguard Orthopedics and Sports Medicine, 291 Independence Drive, Chestnut Hill, MA 02467 (e-mail: kmithoefer@partners.org).

No potential conflict of interest declared.

Articular cartilage injuries affect an estimated 900 000 individuals in the United States every year, resulting in considerable morbidity and disability for affected individuals with a substantial associated burden on the health-care system.<sup>10,49</sup> Treatment of articular cartilage injury in the knee still presents a great therapeutic challenge due to the limited regenerative capacity of articular cartilage.<sup>7,8,28,49</sup> Several options are currently available to the clinician



**Figure 1.** Cartilage repair with the microfracture technique involves several systematic steps, including debridement to a stable cartilage margin (A), careful removal of the calcified cartilage layer (B), and homogeneous placement of microfracture penetrations within the cartilage defect (C), with resultant complete defect fill by a well-anchored mesenchymal clot (D).

treating articular cartilage lesions in the knee, including microfracture, autologous chondrocyte implantation, and osteochondral autograft and allograft transplantation. Although no validated treatment algorithm exists for treating articular cartilage lesions in the knee, the arthroscopic microfracture technique is commonly used as a first-line option and frequently serves as the standard technique against which other cartilage repair procedures are compared. Developed by Steadman in the 1980s, this widely used procedure is generally regarded as safe and effective (Figure 1).<sup>35,45,46,49</sup> Despite its widespread clinical use, no systematic evaluation of the clinical efficacy of the microfracture technique for cartilage repair in the knee is available. A recent analysis of cartilage repair techniques has pointed out the methodological limitations of the available literature on articular cartilage repair.<sup>35</sup> To address the lack of systematic information specifically for the microfracture technique, we performed a comprehensive

analysis of the clinical literature on articular cartilage repair in the knee by this technique. The goal of this systematic analysis was to provide the clinician treating knee articular cartilage injuries with an objective overview of the current knowledge about the repair cartilage quality and quantity achieved after microfracture and the short- and long-term clinical results associated with this technique. Specific focus was placed on evaluation of methodological quality of the available literature, the parameters that affect clinical outcome after microfracture, and identification of areas requiring further study.

## MATERIALS AND METHODS

For this systematic review, we performed a literature search to identify any published and unpublished clinical studies of microfracture, using the MEDLINE, MEDLINE preprints, EMBASE, CINAHL, Life Science Citations, and

the British National Library of Health, including the Cochrane Central Register of Controlled Trials (CENTRAL) medical electronic databases. The search period was January 1, 1966 to October 31, 2007. The medical databases were searched using the terms “microfracture,” “marrow stimulating technique,” “articular cartilage repair,” “articular resurfacing,” “articular drilling,” “intrinsic repair enhancement,” “chondroplasty,” “chondral defect,” “condylar lesion,” “condyle lesion,” “patellofemoral lesion,” “trochlear defect,” “knee lesion,” “joint surface defect,” and “JSD.” The search included only English and German sources because translation services for other languages were not readily available. In addition, the bibliographies of relevant studies and reviews on articular cartilage repair were manually searched. Any study reporting clinical information on articular cartilage repair by the microfracture technique was selected for primary review. Specific attention was placed on identifying studies that described parameters of clinical efficacy for cartilage repair. Efficacy was defined as the ability to produce hyaline repair cartilage tissue and improve clinical knee function.

A total of 221 clinical studies on microfracture were identified and their abstracts were evaluated in a primary screening by 2 independent reviewers. Of these studies, only studies reporting on microfracture for International Cartilage Repair Society (ICRS) grade III or IV chondral or osteochondral defects of the knee (femoral condyle, tibia, and patellofemoral) were included, while studies in patients with osteonecrosis of the knee were excluded. Studies involving patients treated with microfracture alone or in comparison with any other surgical treatment of articular cartilage defects of the knee were included. Studies with or without concomitant adjuvant procedures were accepted. All prospective randomized controlled studies (Levels I and II) were included in the study. Prospective or retrospective studies with or without control groups (Levels III and IV) were accepted for inclusion into the study if they provided clinical outcome measures in the knee with follow-up of  $\geq 2$  years after surgery or qualitative or quantitative data on repair cartilage on MRI. Studies were also included if they provided second-look or histologic results  $\geq 1$  year after surgery. Lower-level studies were included because inclusion of only the few available high-level studies would have biased against potentially valuable studies that did not report outcomes with a high level of evidence. Studies with follow-up rates of less than 70% were excluded to reduce transfer and exclusion bias.

Thirty-two studies met these primary inclusion criteria and full-text articles of these studies were obtained for secondary review. After secondary review, 3 of the studies were excluded as they represented duplicate publications. One study was excluded for a follow-up rate of less than 70%. From the remaining 28 studies, 2 independent reviewers systematically extracted data on study characteristics and design, level of evidence, demographic parameters, cartilage defect characteristics, surgical technique and rehabilitation protocol, associated surgical procedures, clinical follow-up, and treatment outcomes. Specific focus was placed on extracting data describing clinical efficacy of articular cartilage repair, including clinical knee function

TABLE 1  
Coleman Methodology Score

Part A	
1. Study size	0-10 points
2. Mean follow-up	0-5 points
3. Number of surgical procedures	0-10 points
4. Type of study	0-15 points
5. Diagnostic certainty	0-5 points
6. Description of surgical procedure	0-5 points
7. Description of postop rehabilitation	0-10 points
Total points, part A	0-60 points
Part B	
1. Outcome criteria	0-10 points
2. Outcome assessment	0-15 points
3. Description of selection process	0-15 points
Total points, part B	0-40 points
Total Coleman Score	0-100 points

scores, qualitative and quantitative repair cartilage data on postoperative MRI, or macroscopic or microscopic information of repair cartilage tissue. To assess for the methodological quality of the collected data, the modified Coleman Methodology Scores and subscales were determined for each included study.<sup>9,21</sup> The Coleman Methodology Score assesses the methodology of clinical studies by use of subscores assigned 10 specific criteria (study size, mean duration of follow-up, number of surgical procedures, type of study, diagnostic certainty, description of surgical procedure, postoperative rehabilitation, outcome measures, outcome assessment, and selection process). Grading of studies is done by assigning a score for each criterion, with a resultant score between 0 and 100. A score of 100 indicates the highest study quality. The modified Coleman Methodology Score has been previously used for analysis of methodological quality of cartilage repair studies<sup>21</sup> (Table 1).

Functional outcome measures included in the reviewed studies included the Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index, visual analog scale (VAS), modified Cincinnati knee score, International Knee Documentation Committee (IKDC) form, Lysholm-Gillquist score, Short Form-36 (SF-36) health survey, Marx activity rating scale, Tegner activity scale, ICRS clinical cartilage injury evaluation system score, activities of daily living (ADL) score, Baumgaertner score, Hospital for Special Surgery score, Meyers score, Japanese Orthopaedic Association knee score, and knee injury and osteoarthritis outcome score (KOOS). Although all these outcome measures are established for assessment of knee function, only the Lysholm-Gillquist score has been specifically validated for clinical knee function evaluation of chondral disorders.<sup>24</sup>

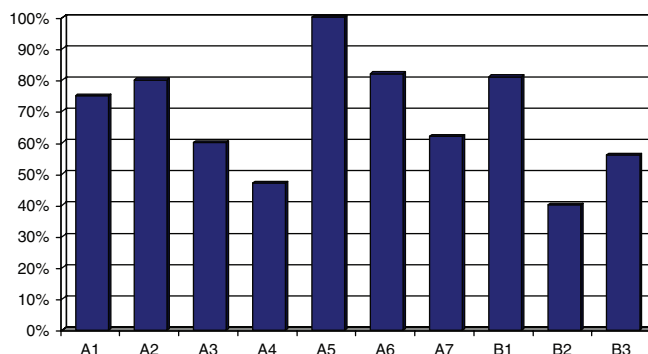
Besides clinical outcome scores, several parameters were selected that provided quantitative or qualitative information about the repair cartilage tissue. Because macroscopic tissue quality has been shown to affect clinical results from cartilage repair, macroscopic assessment of the repair cartilage at second-look arthroscopy was included in the evaluation of clinical effectiveness of cartilage repair from microfracture.<sup>22,48</sup> In addition, histologic characteristics of biopsy specimens taken from the repair cartilage tissue

were included in the assessment.<sup>27</sup> Histologic parameters included surface appearance, matrix characteristics, type II collagen content, cell distribution, and subchondral bone appearance. Because the appearance of the repair cartilage tissue on postoperative MRI has been found to correlate with knee function after microfracture,<sup>25,26,36</sup> postoperative MRI evaluation of the cartilage repair tissue was also included. Magnetic resonance imaging criteria included quantitative filling of the defect, quality of the repair tissue, peripheral integration with the surrounding articular cartilage, and the effect of microfracture on subchondral bone. Adverse events, complications, and rates of treatment failure were recorded from the included studies. Failure was defined as need for revision surgery. The data were independently checked against the original papers using a standard quality-control procedure. Any differences of opinion between the original reviewer and quality-control reviewer were resolved by discussion and reference to the study paper. The data were analyzed using established statistical software. Differences between independent parameters were evaluated using the Kruskal-Wallis test. Relationships between variables were tested by using Pearson's coefficient of correlation ( $r$ ). Differences were considered significant with a  $P < .05$ . Data are presented as mean  $\pm$  the standard error of the mean.

## RESULTS

Twenty-eight studies were included, describing 3122 patients (Table 2). The average postoperative follow-up was  $41 \pm 5$  months (range, 12-136 months), with an average follow-up rate of 91%. The mean number of study subjects was  $110 \pm 42$  (range, 7-1200 patients). Six studies were randomized controlled studies, 1 was a prospective cohort study, 12 were prospective case series, and 9 were retrospective case series. Level-of-evidence ratings showed 4 Level I, 2 Level II, and 22 Level IV studies. The average Coleman Methodology Score was  $58.2 \pm 3.6$  (range, 22-97) and was significantly higher than the Coleman Methodology Score reported for cartilage repair in general ( $43.5 \pm 1.6$ ,  $P < .0001$ ) by Jakobsen et al.<sup>21</sup> Coleman Methodology Scores correlated with the year of publication ( $r = .467$ ,  $P = .012$ ) and inversely correlated with the level-of-evidence rating ( $r = -.584$ ,  $P = .001$ ). Coleman Methodology Scores were highest for diagnostic certainty, follow-up, and outcome criteria, while they were low for study design, outcome assessment process, and study selection (Figure 2).

There was heterogeneity in the study populations with regard to lesion characteristics, concomitant procedures, degrees of joint degeneration, and age (Table 3). Although the majority of studies included acute, single, chondral defects, several studies described patients with both acute and chronic defects, chondral and osteochondral cartilage lesions, or single and multiple defects. Most studies had average lesion sizes of less than  $4 \text{ cm}^2$ , but individual defect size ranged between  $0.1$  to  $20 \text{ cm}^2$ . The majority of the studies also included defects in both the femorotibial and patellofemoral compartments. Although a third of the reviewed studies were



**Figure 2.** Average Coleman Methodology Subscores. A1, study size; A2, follow-up; A3, concomitant surgical procedures; A4, study design; A5, diagnostic certainty; A6, surgical technique; A7, rehabilitation; B1, outcome criteria; B2, procedure of outcome assessment; B3, patient selection process. As maximal scores vary between 0 and 15 points between individual subscores, results are displayed as percentage of maximum value for comparability.

**TABLE 2**  
Review Demographics

Number of included studies	28
Number of patients	3122
Patients with follow-up >5 years	1524
Average follow-up	$41 \pm 5$ months (range, 12-136)
Average age	$39 \pm 10$ years (range, 24-65)
Average number of study subjects	$110 \pm 42$ (range, 7-1200)
Average lesion size	$3.0 \pm 0.8 \text{ cm}^2$ (range, 0.1-20)

limited to cartilage defects in the femorotibial compartment, no single study was available that specifically evaluated the results of microfracture for patellofemoral cartilage defects. Many studies also included patients with concomitant procedures such as meniscal surgery or ligament reconstructions. Only 2 studies reported whether the meniscal injury was in the same compartment as the cartilage defect. The average age of the individual studies ranged between 24 and 65 years (mean  $39 \pm 2$  years), with significantly higher age in studies focusing on patients with chronic degenerative defects ( $54 \pm 2.8$  years,  $P < .001$ ). Only 10 studies reported measurement of body mass index and only 6 studies specifically recorded preoperative duration of symptoms or the number of prior surgeries. Detailed rehabilitation protocols were described in 21 (75%) of the reviewed studies. Sixty-six percent described separate protocols for patellofemoral and femoral defects. Continuous passive motion was documented in 70% and used between 3 and 8 hours a day for 4 to 8 weeks. Protected weightbearing was used between 4 and 8 weeks postoperatively for femoral lesions.

Fifteen different knee outcome scales were used for outcome evaluation. Nineteen studies used one or more validated outcome scales. Five studies used scores for functional criteria such as pain, swelling, and the ability to perform strenuous work or athletic activity. The most commonly

TABLE 3  
Distribution of Study Characteristics

Characteristic	Number (Percentage)
Defect type (acute/chronic)	
Acute	11 (39)
Acute + chronic	10 (36)
Chronic	5 (18)
Not specified	2 (7)
Defect type (chondral/osteochondral)	
Chondral	22 (79)
Chondral + osteochondral	4 (14)
Osteochondral	0 (0)
Not specified	2 (7)
Defect location	
Femorotibial	8 (29)
Femorotibial + patellofemoral	19 (68)
Patellofemoral	0 (0)
Not specified	1 (4)
Defect number	
Single defects	14 (50)
Single + multiple defects	9 (32)
Not specified	5 (18)
Average defect size	
<2 cm <sup>2</sup>	3 (11)
2-4 cm <sup>2</sup>	14 (50)
>4 cm <sup>2</sup>	4 (14)
Not specified	7 (25)
Concomitant Procedures <sup>a</sup>	
None	14 (50)
Additional procedure	11 (39)
Not specified	3 (11)
Meniscal surgery	9 (32)
Ligament reconstruction	6 (21)
High tibial osteotomy	3 (11)

<sup>a</sup>Some studies listed >1 concomitant procedure.

used outcome scales used were the Lysholm-Gillquist score (n = 11 [39%]) and the Tegner activity score (n = 9 [32%]). The average postoperative Lysholm score was 80.8 ± 6 and the average Tegner score was 4.8 ± 0.8 at the time of last follow-up. Improved knee function scores were reported in all (24 of 24) studies using quantitative outcome measures.<sup>#</sup> Improvement was reported as early as 6 months, with the greatest overall improvement consistently occurring during the first 24 months after microfracture (Table 4).<sup>\*,\*\*</sup> Two recent randomized studies demonstrated that functional improvement from microfracture during the first 24 months may be more rapid than with autologous chondrocyte transplantation but less rapid than with osteochondral autograft.<sup>17,23</sup>

Long-term clinical results (≥5 years) after microfracture were reported in 5 studies (1524 patients).<sup>12,15,22,43,46</sup> One study was randomized, 2 were prospective case series, and 2 were retrospective case series. The average Coleman Methodology Score was 59 ± 19 (range, 40-88). Improved knee function was reported in 67% to 86% of

TABLE 4  
Overview of Reported Clinical Results  
After Microfracture

Clinical knee function	
Short-term clinical improvement rate (≤24 mo)	75%-100%
Long-term clinical improvement rate (>24 mo)	67%-86%
Functional deterioration (>24 mo) <sup>a</sup>	47%-80%
Magnetic resonance imaging	
Complete cartilage fill	18%-95%
Poor cartilage fill	17%-57%
Complete peripheral integration	4%-8%
Subchondral bone hypertrophy	25%-49%
Macroscopic/microscopic repair cartilage assessment	
Macroscopic grading normal/near normal	45%-77%
Histology:	
Fibrocartilage	33%-57%
Fibrohyaline hybrid tissue	39%-64%
Complication rate	
Serious procedure-related complications	0%-13%
Failure/revision rate	
Less than 24 mo	2.5%
After 24 mo	2%-31%

<sup>a</sup>Despite deterioration, clinical function still better than before microfracture.

patients at an average of 6 to 7 years after microfracture, with pain and swelling being the parameter with the greatest improvement.<sup>12,15,43,46</sup> There was no statistical correlation between long-term improvement rate and level of evidence ( $r = .242$ ,  $P = .695$ ) and Coleman scores ( $r = .031$ ,  $P = .961$ ). The study with the longest average follow-up of 11 years demonstrated that 32% of patients were pain free, 54% had mild pain, and 14% had moderate pain at final follow-up.<sup>46</sup> Randomized comparison of microfracture with autologous chondrocyte transplantation showed no significant difference of functional scores between the 2 repair techniques at 5 years.<sup>22</sup>

Two studies reported that the initial functional improvement observed during the first 2 years after microfracture was maintained.<sup>22,46</sup> In contrast, 7 studies reported deterioration of initial functional improvement in 47% to 80% of patients between 18 and 36 months after microfracture.<sup>4,15,17,25,26,36,37</sup> However, the decreased functional scores were still higher than the preoperative scores. One study noted that decreasing functional scores were seen in all patients with poor repair cartilage fill volume after microfracture.<sup>36</sup>

Five studies in 251 patients have reported specifically the results of microfracture in degenerative cartilage defects with average Coleman scores of 50 ± 6.<sup>2,31-33,47</sup> The mean age of these patients was significantly higher than in studies with mixed or acute cartilage injuries ( $P < .001$ ). Two studies reported on isolated microfracture and 3 studies on microfracture combined with high tibial osteotomy. Although all studies demonstrated improvement of knee scores at 1 to 5 years after microfracture, 1 study showed no significant difference of clinical outcome between combined treatment and high tibial osteotomy alone.<sup>31</sup>

<sup>#</sup>References 1-4, 12, 13, 15, 17, 22, 23, 25, 26, 29, 31-33, 36, 37, 39, 42-44, 46, 47.

<sup>\*\*</sup>References 4, 15, 22, 23, 25, 26, 36, 37, 42-44, 46.

TABLE 5  
Factors Affecting Outcome After Microfracture

Factors	Better Results With
Age	<40 years
Duration of symptoms	<12 months
Lesion size	<4 cm <sup>2</sup>
Body mass index	<30 kg/m <sup>2</sup>
Preoperative activity level	Tegner score >4
Previous surgery	Primary microfracture
Repair cartilage volume	Good defect fill (>66%)

### Factors Affecting Functional Outcome

Younger age resulted in better clinical outcome scores and better repair cartilage fill on MRI. The reported age threshold varied between 30 and 40 years.<sup>17,22,23,26,36,37,46</sup> Preoperative intervals of less than 12 months were associated with better postoperative scores and macroscopic repair cartilage grading.<sup>4,12,36,37</sup> Microfracture was most effective as a first-line procedure, while its results in a salvage situation were less predictable.<sup>12,37</sup> Patients with lesions <4 cm<sup>2</sup> had better knee function scores,<sup>12,17,22,23,37,46</sup> with an even smaller threshold (<2 cm<sup>2</sup>) reported for the demanding athletic population.<sup>17,37</sup> Although some authors reported better results with cartilage defects on the femoral condyles,<sup>26</sup> others found no effect or worse outcomes for lesions in the central weightbearing femoral condyle.<sup>17</sup> Body mass index inversely correlated with knee function after microfracture, with worst outcomes observed for a body mass index >30 kg/m<sup>2</sup>. Higher body mass index was also associated with worse repair cartilage volume.<sup>36</sup> Finally, higher preoperative activity levels (Tegner score >4) improved knee scores and athletic ability after microfracture (Table 5).<sup>4,23,37,39</sup>

### Magnetic Resonance Imaging Results

Magnetic resonance imaging was used in 9 studies (361 patients) to evaluate cartilage repair at 12 to 72 months after microfracture.<sup>††</sup> Two studies were randomized controlled, 6 were prospective case series, and 1 was a retrospective case series. Average Coleman Methodology Scores of these studies were 59 ± 21 (range, 22-86). There was notable variability in the reported repair cartilage fill grade between studies. Complete cartilage fill was reported between 18% and 95%, while poor fill was observed in 17% to 57% of the imaging studies (Table 4).<sup>1,6,17,36,40</sup> There was no statistical correlation between fill grade on MRI and methodological quality of the study ( $r = .713$ ,  $P = .176$ ). Integration with the surrounding normal cartilage showed persistent gaps in 92% to 96% and complete integration in only 4% to 8%. Subchondral edema was present in all cases preoperatively and resolved over time in patients with good fill but failed to diminish with poor fill grade (Figure 3).<sup>6,30,36</sup> Subchondral bony overgrowth occurred in 25% to 49% and subchondral cyst formation was observed in 33% of patients (Figure 4).<sup>6,17,36</sup> Repair cartilage fill on MRI was

better with age <40 years, femoral condyle lesions,<sup>25,26</sup> smaller defect size,<sup>13</sup> and lower body mass index.<sup>36</sup> Importantly, fill grade on MRI positively correlated with functional outcome scores.<sup>25,26,36</sup> In 1 study, good fill grade was always associated with improved knee function, whereas improvement occurred in only 25% of patients with poor fill grade.<sup>36</sup>

### Macroscopic and Microscopic Repair Cartilage Evaluation

Second-look arthroscopy was performed in 9 studies (366 patients). Three of the studies were randomized controlled, 1 was a prospective cases series, and 5 were retrospective case series with an average Coleman score of 56 ± 7 (range, 22-88).<sup>‡‡</sup> Normal or nearly normal macroscopic cartilage repair grading was seen in 45% to 77% of defects at 8 to 24 months after microfracture.<sup>17,22,23,40</sup> Fibrillated tissue was described in 16% and fragmented fill in 18%.<sup>12</sup> Poor repair cartilage coverage with exposed subchondral bone was present in 5% to 35% of second-look arthroscopies.<sup>4,17,31,40,41</sup> Macroscopic scores at 2 years after microfracture were not significantly different from those for defects treated with autologous chondrocyte transplantation.<sup>22</sup> Interestingly, a significant association was observed between the macroscopic appearance at second-look arthroscopy after 2 years and the risk for treatment failure at 5 years.<sup>22</sup>

Histologic data from human studies after microfracture were reported in only 6 studies involving 138 biopsies and were limited to the first 24 months after microfracture.<sup>2,15,17,22,23,31,42</sup> The average Coleman score was 73 ± 15 (range, 54-97). Fibrocartilage alone was found in 33% to 57% and hybrid fibrohyaline cartilage with variable amounts of type II collagen content was described in 39% to 64%.<sup>2,15,17,23,31</sup> There was a statistical trend toward fibrocartilage repair in the microfracture group compared to autologous chondrocyte implantation ( $P = .08$ ).<sup>22,23</sup> Compared with characterized chondrocyte implantation, microfracture produced significantly lower histological scores for type II collagen and matrix proteoglycan content.<sup>42</sup> The histological repair quality showed no statistical correlation with clinical outcome scores but better histological quality was associated with significantly lower failure rate.<sup>22,23</sup>

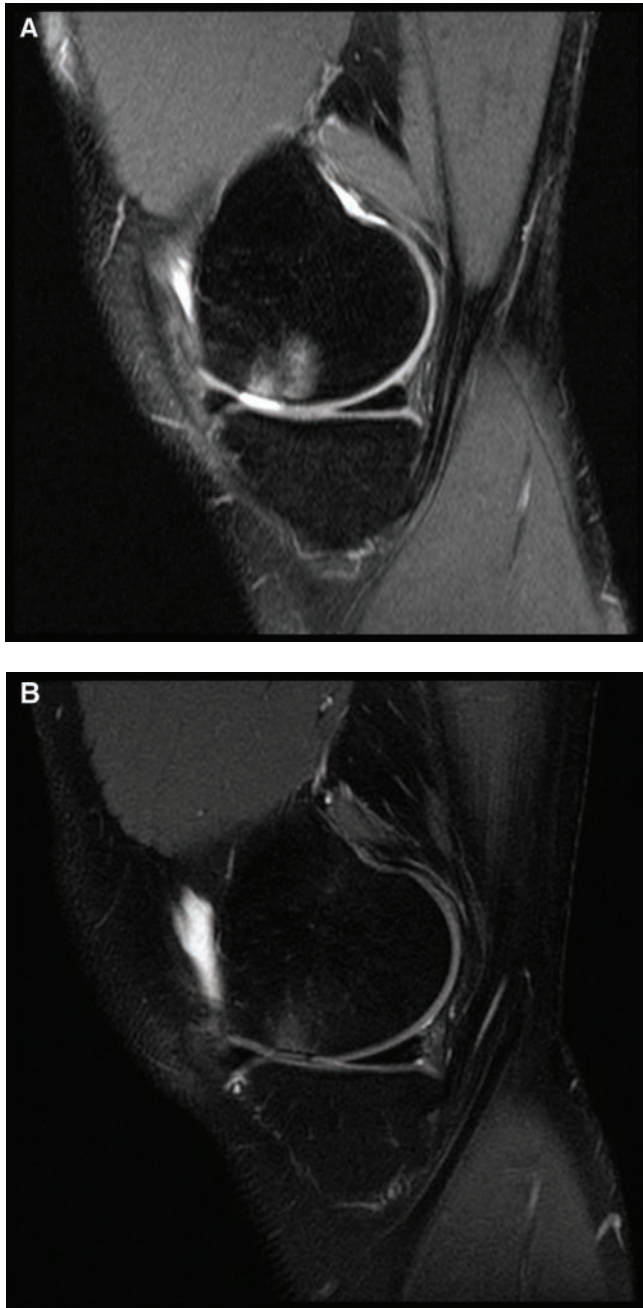
### Complications and Failures

Complications after microfracture were generally rare.<sup>§§</sup> Steadman et al<sup>43,46</sup> described no perioperative complications related to the surgical procedure in 1275 patients. Similarly, 3 randomized, controlled studies found no procedure-related serious adverse effects after microfracture.<sup>17,22,23</sup> One study reported adverse effects such as arthralgia (57%), effusion (5%), and crepitation (1.6%), with serious procedure-related adverse effects in 13%.<sup>41</sup> Local septic complications and deep vein thrombosis were observed in up to 2%.<sup>15,17,23,29</sup> Arthrofibrosis requiring lysis of adhesions occurred in up to

††References 1, 6, 13, 15, 17, 25, 26, 30, 36, 40.

‡‡References 2, 4, 12, 15, 17, 22, 23, 40, 41.

§§References 15, 17, 22, 23, 29, 33, 37, 43, 46.



**Figure 3.** Magnetic resonance image of a cartilage defect of the femoral condyle before microfracture (A) and 6 months postoperatively (B), showing good repair cartilage fill grade and decreased subchondral bone edema.

16% of patients with degenerative defects treated with microfracture and high tibial osteotomy.<sup>33</sup>

Failure after microfracture was variable and time-dependent. In randomized studies, the early revision rate was 2.5% at 2 years and increased to 23% to 31% between 2 and 5 years after microfracture (Table 4). Some other case series reported lower revision rates of 2% to 7% at 4 to 11 years after microfracture.<sup>15,29,46</sup> In degenerative

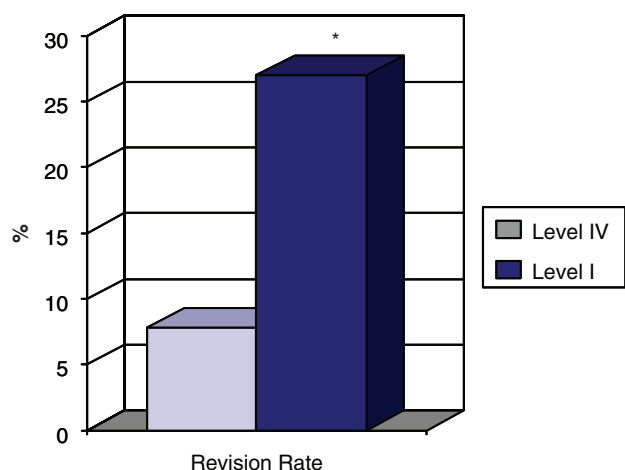


**Figure 4.** Sagittal magnetic resonance image of a cartilage defect of the femoral trochlea 12 months after microfracture, demonstrating poor cartilage fill volume and an irregular subchondral bone plate with overgrowth.

defects, the early revision rate was 4% to 6% at 2 years and increased to 9% to 16% at 5 years.<sup>33,47</sup> Revision rates were significantly higher in Level I studies compared to Level IV studies ( $P = .046$ ) (Figure 5), with an inverse statistical correlation between revision rate and level of evidence ( $r = -.901$ ,  $P = .002$ ). Revisions were reported at a mean of 8 to 38 months after microfracture.<sup>17,22,33</sup> Evaluation of the defects at the time of revision showed absent or incomplete fill of the defect with fragmented or detached fibrocartilage in 60% to 89%. Importantly, good macroscopic repair cartilage quality significantly reduced the risk for subsequent revision and no revisions were required in knees with the best histological repair cartilage quality.<sup>22,23</sup>

## DISCUSSION

Microfracture is one of the most frequently used techniques for repair of articular cartilage defects in the knee. Although this surgical technique is often used as a standard against which other cartilage techniques are compared, systematic analysis of the published results is still absent. Twenty-eight clinical studies describing more than 3000 patients were available for this review, more than for any other single cartilage repair technique.<sup>21</sup> Average Coleman Methodology Scores were significantly better for microfracture studies than for cartilage repair studies in general, indicating an acceptable overall validity of the combined results on microfracture.<sup>21</sup> Although the quality of the currently available data on microfracture is still limited, this review was able to



**Figure 5.** Difference of average reported revision rate after microfracture between high and low methodological levels of evidence. \* $P < .05$ .

identify several areas of high agreement and variability between studies. High consensus was found between studies for the rate of clinical improvement after microfracture, while high variability was observed for repair cartilage fill grade. The observed variability may be a reflection of the heterogeneity of the study populations or may have resulted from the different study quality and designs. Our review demonstrates that the quality of clinical studies on microfracture has increased over time, confirming that the importance of methodological quality is increasingly recognized.<sup>17,21-23,42</sup> This systematic review identifies the areas that require specific further investigation and provide the basis for future prospective study of the microfracture technique.

Most studies used established knee outcome measures for assessment of knee function after microfracture. The Lysholm score was the most frequently used outcome measure and has been validated for cartilage repair.<sup>24</sup> It is not known if using outcome instruments that are not specifically validated for cartilage repair affects the discriminative power of the reviewed studies on cartilage repair. Further systematic study is required to assess the reliability and responsiveness of most established knee outcome scores for evaluation of articular cartilage injury and repair. Systematic evaluation should include comparison of clinical function scores with validated macroscopic repair scores such as ICRS and Oswestry scores.<sup>48</sup> The methodological quality of the studies included in this review was supported by the high Coleman Methodology subscores for outcome criteria, study size, and follow-up, which helped to limit both detection and transfer bias. However, low Coleman subscores in other areas pointed out some of the methodological study limitations of this review. Low subscores for study type resulted from the limited number of available randomized controlled studies on microfracture. Limited subscores for description of the selection process indicated the possible presence of selection bias. Although the heterogeneity between the study populations and rehabilitation protocols introduced the potential for performance bias, we felt it was appropriate for a systematic

review. The majority of the studies included only isolated chondral defects and a mean defect size  $<4 \text{ cm}^2$ , which falls within the recommended lesion size for microfracture.<sup>35,49</sup> However, most studies failed to differentiate between femorotibial and patellofemoral lesions, with only a third of the studies reporting on isolated femorotibial lesions. Interestingly, none of the studies evaluated patellofemoral defects alone. It is unclear whether separating patients based on their lesion location may be important as some cartilage repair studies have found that results may vary depending on the lesion location,<sup>5,26</sup> while other authors have not found a significant effect of lesion location.<sup>46</sup> Future studies are needed to specifically evaluate this aspect and to particularly investigate microfracture in isolated patellofemoral cartilage lesions. Many studies included patients with concomitant meniscal or ligamentous procedures, which raises the concern for performance bias. However, half the studies in this review had no concomitant surgical procedures. It has been pointed out that large, homogeneous cartilage repair populations are hard to obtain because confounding surgical factors, such as ligament injury, are often involved in the development of the cartilage defects.<sup>21</sup> Although the heterogeneity is of potential methodological concern, it may not be clinically relevant because several studies have failed to detect a statistical effect of concomitant procedures for either microfracture or other cartilage repair procedures.<sup>15,22,23,34,38,43</sup> A potential benefit of the heterogeneity of the included studies is that it improves external validity and allows for generalization of the results of this review. This is supported by the fact that despite the observed variability, several consistent findings were demonstrated in this review. Nevertheless, large, well-designed, multicenter studies are needed to achieve adequate study populations and power that allows for clean comparison of isolated defects with subpopulations with combined confounding factors.

Rehabilitation protocols after microfracture were variable, but the majority of studies used similar protocols for continuous passive motion (6-8 hours/day for 6 weeks) with protected weightbearing for 6 weeks for femoral defects and immediate full weightbearing for patellofemoral defects. However, rehabilitation protocols are mostly empirical; very limited data are available on rehabilitation protocols after microfracture and the effect of continuous passive motion and weightbearing status has not been evaluated systematically. The beneficial effect of joint motion on cartilage nutrition and metabolism is well documented.<sup>12</sup> Clinical studies have shown that continuous passive motion significantly increases the rate of macroscopic grading of the treated defect from 55% to 85%.<sup>41</sup> However, in defects  $<1 \text{ cm}^2$ , other investigators have found no significant difference in outcome with or without the use of continuous passive motion or protected weightbearing.<sup>29</sup> The importance of postoperative rehabilitation after microfracture is well recognized and systematic prospective studies are needed to allow for development of evidence-based postoperative protocols that optimize postoperative outcome from microfracture.

Improvement of knee function scores was described in all reviewed studies during the first 24 months after microfracture, attesting to its excellent short-term efficacy. Controversy

exists about the durability of the initial improvement. Increasing evidence suggests a decline of the initial functional improvement after 2 years, although average knee function scores remain above preoperative levels.<sup>17,25,26,36,37</sup> This functional decline is consistent with the decline in the long-term improvement rate to 67% to 85% and the increasing failure rate that has been observed between 2 and 5 years after microfracture.<sup>12,14,15,23,43,46</sup> The reason for this functional decline is not completely understood. This review was able to identify several factors that affected knee function after microfracture. Repair cartilage fill volume was found to play a critical role in the durability of knee functional improvement as decreasing knee function consistently occurred with poor fill volume. However, decreasing knee function was observed not only in patients with poor fill grade; other factors such as quality of the repair tissue, peripheral integration with the surrounding articular cartilage, and subchondral changes must be considered. Other parameters that have been found to affect knee function included age, lesion location, macroscopic repair cartilage quality, preoperative duration of symptoms, preoperative activity level, number of preoperative surgeries, and body mass index (Table 5).<sup>4,22,23,25,26,36,37</sup> Carefully designed long-term studies are needed that evaluate which factors contribute to the functional deterioration after microfracture. Better understanding of these factors allows for preoperative identification of patients who will likely not show permanent improvement from microfracture. This will help to avoid early failure and promote the primary use of alternative cartilage repair techniques in these cases. The recent observation that primary marrow stimulation, including microfracture, can increase combined failure rate from secondary autologous chondrocyte transplantation from 17% to 50% suggests that primary microfracture may have detrimental effects on subsequent cartilage repair attempts with other techniques. The reasons for this effect are not clear and require further investigation. These findings emphasize the importance of clearly defining the indications for microfracture and the development of validated treatment algorithms for cartilage repair.<sup>16</sup>

Magnetic resonance imaging demonstrated marked variability of repair cartilage volume within the defects after microfracture, which may have been a result of the heterogeneous study populations. However, even within the more homogeneous study populations of individual studies, significant variability of defect fill was observed.<sup>17,36,42</sup> Body mass index was found to inversely correlate with fill grade and may have contributed to the observed variation of repair cartilage fill grade.<sup>36</sup> Similarly, lesion location and age have been shown to significantly affect repair cartilage fill grade.<sup>25,26</sup> Fill grade on MRI also affected durability of functional improvement.<sup>36</sup> We found that a similar proportion of patients showed poor fill grade on MRI and exposed bone on second-look arthroscopy.<sup>4,17,36</sup> This finding is supported by the previously reported good correlation between MRI and second-look arthroscopy.<sup>18,40</sup> Our finding suggests that a subpopulation of patients exists that does not produce sufficient cartilage repair volume after microfracture. Displacement of the initially fragile clot from the defect has been described in experimental studies and may offer a possible reason for the

lack of filling and persistent subchondral bone exposure observed in this subpopulation.<sup>19</sup> Routine postoperative MRI is recommended to identify this subpopulation early and to promote revision cartilage repair procedures. Incomplete peripheral integration with the surrounding native articular cartilage was seen in the majority of the patients (92% to 96%) and was worst with poor fill grade. Limited peripheral integration is important because it increases the susceptibility to shear forces and raises the potential for repair cartilage deterioration and functional decline. Technical considerations may play a role as recent experimental studies have suggested that insufficient removal of the calcified cartilage and debridement of the peripheral cartilage negatively affects repair cartilage volume and integration.<sup>11</sup> However, excessive debridement of the calcified cartilage may stimulate subchondral bone overgrowth, which indicates that microfracture requires careful attention to technical detail to optimize its clinical results and may be more technically demanding than generally assumed.<sup>34,35,44</sup> Technical variations may also contribute to the observed variability in the repair cartilage fill. The reviewed literature suggests that complete fill of the lesion may not be necessary for short-term functional improvement, but that enhancing fill increases the rate for durable clinical improvement. Further prospective studies using routine MRI at defined postoperative intervals are needed to provide systematic longitudinal information on defect fill grade and peripheral integration after microfracture. Subchondral bone overgrowth after microfracture was observed in 25% to 49%.<sup>6,36</sup> This phenomenon leads to relative thinning of the overlying repair cartilage and may limit durability and long-term outcome from microfracture. So far, only descriptive information is available on this phenomenon in humans and the understanding of its origin is still limited. Further systematic study is required to evaluate the pathophysiology of subchondral bone overgrowth and its clinical effect on repair cartilage and knee function.

Second-look and histologic data in humans are limited to the first 24 months after microfracture. The available macroscopic and microscopic data were limited in multiple aspects and more systematic, long-term information would be desirable. However, the morbidity of scheduled second-look arthroscopies and biopsy-related injury to the repair cartilage limit ethical justification and achievability of systematic histologic investigations. Despite the limitations, the available macroscopic and microscopic data demonstrate several consistent aspects. Microfracture was not effective in restoring normal hyaline cartilage but rather resulted primarily in fibrocartilage or hybrid repair tissue with variable proteoglycan and type II collagen content. Despite the limited tissue quality, short-term function improved in all studies. This suggests that histologic tissue quality affects short-term functional improvement less than repair cartilage fill volume. This is supported by the reported lack of association between histologic repair tissue quality and functional outcome scores.<sup>22,23</sup> However, the same study showed that no long-term failures occurred in knees with the best repair cartilage quality, suggesting that the repair tissue quality is more important for long-term functional outcome.<sup>22</sup> Inferior biomechanical quality of fibrocartilage contributes to tissue degradation over time

and may be a factor in the observed functional decline and increasing failure rate.<sup>7,8,20</sup> This is supported by the very poor repair tissue quality described in defects undergoing revision cartilage repair after failing microfracture.<sup>17,29</sup>

Serious, procedure-related adverse events after microfracture were consistently rare, confirming the excellent patient safety and low morbidity from this minimally invasive technique. Reported failure rates were variable but direct comparison between studies was prevented by inconsistent failure definitions between studies. Therefore, the need for revision surgery or failure to improve clinically was used to describe failure in this review. Revision surgery was required in 2% to 31%, with an increasing revision rate after 2 years.<sup>17,22,46</sup> This study suggests that the variability of these revision rates may have resulted from the different methodological level of evidence in the reviewed studies because higher revision rates were observed in studies with higher methodological quality.<sup>17,22,23,46</sup> The variability of the revision rate may also reflect the variability of repair cartilage fill and quality after microfracture. This is consistent with the finding that revision was performed primarily in patients with limited repair tissue volume and quality, while defects with the best repair tissue quality required no revisions.<sup>17,22,29</sup> Similar to this revision rate, lack of clinical improvement or worsening symptoms were described in up to a third of patients 3 to 11 years after microfracture.<sup>4,39,43,46</sup> Further systematic and well-designed study is warranted to better understand the factors that can lead to failure after microfracture, to clearly define the indications of this technique, and to develop approaches that can help to optimize the results from cartilage repair.

In conclusion, our review shows that microfracture is a minimally invasive and safe technique for articular cartilage repair in the knee. This technique does not restore normal hyaline cartilage but primarily results in fibrous or hybrid repair cartilage tissue with variable repair tissue volume. Despite this shortcoming, excellent short-term functional improvement is consistently observed. Decreasing knee function after initial improvement and increasing failure rate over time in some patients indicate the long-term clinical limitations of the current technique. Although the current review provides helpful and comprehensive clinical information for the clinician, it is important to recognize that the scientific level of evidence of the currently available literature on microfracture is still limited. Further systematic, well-designed, longitudinal studies are needed to outline which factors affect cartilage fill grade and histological quality and which patients will benefit most from microfracture.

## REFERENCES

- Bachmann G, Basad E, Lommel D, Steinmeyer J. MRI in the follow-up after MACI or microfracture. *Radiologe*. 2004;44:773-782.
- Bae DK, Yoon KH, Song SJ. Cartilage healing after microfracture in osteoarthritic knees. *Arthroscopy*. 2006;22:367-374.
- Basad E, Sturz H, Steinmeyer J. The treatment of chondral defects with MACI or microfracture: first results of a controlled clinical trial. *Orthopädische Praxis*. 2004;40:6-10.
- Blevins FT, Steadman JR, Rodrigo JJ, Silliman J. Treatment of articular cartilage defects in athletes: an analysis of functional outcome and lesion appearance. *Orthopedics*. 1998;21:761-767.
- Brittberg M, Lindahl A, Nilsson A, Ohlsson C, Isaksson O, Peterson L. Treatment of deep cartilage defects in the knee with autologous chondrocyte transplantation. *N Engl J Med*. 1994;331:889-895.
- Brown WE, Potter HG, Marx RG, Wickiewicz TL, Warren RF. Magnetic resonance imaging appearance of cartilage repair in the knee. *Clin Orthop Relat Res*. 2004;422:214-223.
- Buckwalter JA. Evaluating methods for restoring cartilaginous articular surfaces. *Clin Orthop Relat Res*. 1999;367S:S224-S238.
- Buckwalter JA, Mankin HJ. Articular cartilage: part II, degeneration and osteoarthritis, repair, regeneration, and transplantation. *J Bone Joint Surg Am*. 1997;79:612-632.
- Coleman BD, Khan KM, Maffulli N, Cook JL, Wark JD. Studies of surgical outcome after patellar tendinopathy: clinical significance of methodological deficiencies and guidelines for future studies. *Scand J Med Sci Sports*. 2000;10:2-11.
- Curl WW, Krome J, Gordon ES, Rushing J, Smith BP, Poehling GG. Cartilage injuries: a review of 31,516 knee arthroscopies. *Arthroscopy*. 1997;13:456-460.
- Frisbie DD, Morisset S, Ho CP, Rodkey WG, Steadman JR, McIlwraith CW. Effects of calcified cartilage on healing of chondral defects treated with microfracture in horses. *Am J Sports Med*. 2006;34:1824-1831.
- Gill TJ. The treatment of articular cartilage defects using microfracture and debridement. *Am J Knee Surg*. 2000;13:33-40.
- Gill TJ, MacGillivray JD. The treatment of articular cartilage defects in the knee. *Oper Tech Orthop*. 2001;11:105-107.
- Gobbi A, Kon E, Filardo G. Arthroscopic second generation autologous chondrocyte implantation compared with microfracture in the knee: a prospective comparative study. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(suppl 1):S11.
- Gobbi A, Nunag P, Malinowski K. Treatment of chondral lesions of the knee with microfracture in a group of athletes. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:213-221.
- Minas T, Gomoll AH, Rosenberger R, Royce RO, Bryant T. Increased failure rate of autologous chondrocyte implantation after previous treatment with marrow stimulation techniques. *Am J Sports Med*. In press.
- Gudas R, Kalesinskas RJ, Kimtys V, et al. A prospective randomized clinical study of mosaic osteochondral autologous transplantation versus microfracture for the treatment of osteochondral defects in the knee joint in young athletes. *Arthroscopy*. 2005;21:1066-1075.
- Henderson IJ, Tuy B, Connell D, Oakes B, Hettwer WH. Prospective clinical study of autologous chondrocyte implantation and correlation with MRI at three and 12 months. *J Bone Joint Surg Br*. 2003;85:1060-1066.
- Hoemann CD, Hurtig M, Rossomacha E, et al. Chitosan-glycerol phosphate/blood implants improve hyaline cartilage repair in ovine microfracture defects. *J Bone Joint Surg Am*. 2005;87:2671-2686.
- Hunziker E. Articular cartilage repair: basic science and clinical progress. A review of the current status and prospects. *Osteoarthritis Cartilage*. 2002;10:432-463.
- Jakobsen RB, Engebretsen L, Slauterbeck JR. An analysis of the quality of cartilage repair studies. *J Bone Joint Surg Am*. 2005;87:2232-2239.
- Knutsen G, Drogset JO, Engebretsen L, et al. A randomized trial comparing autologous chondrocyte implantation with microfracture: findings at five years. *J Bone Joint Surg Am*. 2007;89:2105-2112.
- Knutsen G, Engebretsen L, Ludvigsen TC, et al. Autologous chondrocyte implantation compared with microfracture in the knee. A randomized trial. *J Bone Joint Surg Am*. 2004;86:455-464.
- Kocher MS, Steadman JR, Briggs KK, Sterett WJ, Hawkins RJ. Reliability, validity, and responsiveness of the Lysholm knee rating scale for various chondral disorders of the knee. *J Bone Joint Surg Am*. 2004;86:1139-1145.
- Kreuz PC, Erggelet C, Steinwachs M, et al. Is microfracture of chondral defects in the knee associated with different results in patients aged 40 years or younger? *Arthroscopy*. 2006;22:1180-1186.
- Kreuz PC, Steinwachs M, Erggelet C, et al. Results after microfracture of full-thickness chondral defects in different compartments in the knee. *Osteoarthritis Cartilage*. 2006;14:1119-1125.
- Mainil-Varlet P, Aigner T, Brittberg M, et al. Histological assessment of cartilage repair: a report by the Histology Endpoint Committee of the International Cartilage Repair Society (ICRS). *J Bone Joint Surg Am*. 2003;85(suppl 2):45-57.

28. Mandelbaum RB, Browne JE, Fu F, et al. Articular cartilage lesions in the knee. *Am J Sports Med.* 1998;26:853-861.
29. Marder RA, Hopkins G, Timmerman LA. Arthroscopic microfracture of chondral defects of the knee: a comparison of two postoperative treatments. *Arthroscopy.* 2005;21:152-158.
30. Marlovits S, Striessnig G, Resinger CT, et al. Definition of pertinent parameters for the evaluation of articular cartilage repair tissue with high-resolution magnetic resonance imaging. *Eur J Radiol.* 2004;52:310-319.
31. Matsunaga D, Akizuki S, Takizawa T, Yamazaki I, Kuraishi J. Repair of articular cartilage and clinical outcome after osteotomy with microfracture or abrasion arthroplasty for medial gonarthrosis. *Knee.* 2007;14:465-471.
32. Miller BS, Joseph TA, Barry EM, Rich VJ, Sterett WI. Patient satisfaction after medial opening high tibial osteotomy and microfracture. *J Knee Surg.* 2007;20:129-133.
33. Miller BS, Steadman JR, Briggs KK, Rodrigo JJ, Rodkey WG. Patient satisfaction and outcome after microfracture of the degenerative knee. *J Knee Surg.* 2004;17(1):13-17.
34. Mithoefer K, Steadman JR. The microfracture technique. *Tech Knee Surg.* 2006;5:141-148.
35. Mithoefer K, Williams RJ, Warren RF, et al. Chondral resurfacing of articular cartilage defects in the knee with the microfracture technique: surgical technique. *J Bone Joint Surg Am.* 2006;88 (suppl 1, pt 2):294-304.
36. Mithoefer K, Williams RJ, Warren RF, et al. The microfracture technique for the treatment of articular cartilage lesions in the knee: a prospective cohort study. *J Bone Joint Surg Am.* 2005;87:1911-1920.
37. Mithoefer K, Williams RJ, Warren RF, Wickiewicz TL, Marx RG. High-impact athletics after knee articular cartilage repair: a prospective evaluation of the microfracture technique. *Am J Sports Med.* 2006;34:1413-1418.
38. Mithöfer K, Peterson L, Mandelbaum B, Minas T. Articular cartilage repair in soccer players with autologous chondrocyte transplantation: functional outcome and return to competition. *Am J Sports Med.* 2005;33:1639-1646.
39. Passler HH. Microfracture for treatment of cartilage defects. *Zentralbl Chir.* 2000;125:500-504.
40. Ramappa AJ, Gill TJ, Bradford CH, Ho CP, Steadman JR. Magnetic resonance imaging to assess knee cartilage repair tissue after microfracture of chondral defects. *J Knee Surg.* 2007;20:228-234.
41. Rodrigo JJ, Steadman JR, Silliman JJ, Fulstone HA. Improvement of full-thickness chondral defect healing in the human knee after debridement and microfracture using continuous passive motion. *Am J Knee Surg.* 1994;7:109-116.
42. Saris DB, Vanlauwe J, Victor J, et al. Characterized chondrocyte implantation results in better structural repair when treating symptomatic cartilage defects of the knee in a randomized controlled trial versus microfracture. *Am J Sports Med.* 2008;36:235-246.
43. Steadman JR, Briggs KK, Rodrigo JJ, Kocher MS, Gill TJ, Rodkey WG. Outcomes of microfracture for traumatic chondral defects of the knee: average 11-year follow-up. *Arthroscopy.* 2003;19:477-484.
44. Steadman JR, Miller BS, Karas SG, Schlegel TF, Briggs KK, Hawkins RJ. The microfracture technique in the treatment of full-thickness chondral lesions of the knee in national football league players. *J Knee Surg.* 2003;16:83-86.
45. Steadman JR, Rodkey WG, Rodrigo JJ. Microfracture: Surgical technique and rehabilitation to treat chondral defects. *Clin Orthop Relat Res.* 2001;391(suppl):S362-S369.
46. Steadman JR, Rodkey WG, Singleton SB, Briggs KK. Microfracture technique for full-thickness chondral defects: technique and clinical results. *Oper Tech Orthop.* 1997;7:300-304.
47. Sterett WI, Steadman JR. Chondral resurfacing and high tibial osteotomy in the varus knee. *Am J Sports Med.* 2004;32:1243-1249.
48. Van den Borne MP, Rajmakers NJ, Vanlauwe J, et al. International Cartilage Repair Society (ICRS) and Oswestry macroscopic cartilage evaluation scores validated for use in autologous chondrocyte implantation (ACI) and microfracture. *Osteoarthritis Cartilage.* 2007;15:1397-1402.
49. Williams RJ. Articular cartilage repair: clinical approach and decision making. *Oper Tech Orthop.* 2006;16:218-226.

---

For reprints and permission queries, please visit SAGE's Web site at <http://www.sagepub.com/journalsPermissions.nav>