The Biology of Articular Cartilage Injury and the Microfracture Technique for the Treatment of Articular Cartilage Lesions

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Without intervention, articular cartilage injuries have limited ability to heal. The limited capacity for repair of articular cartilage is secondary to 2 primary factors: (1) the avascular nature of the tissue; and (2) the absence of an undifferentiated cell population that can respond to injury. Violation of the subchondral plate, through the microfracture technique, exposes the damaged area to progenitor cells that reside within the subchondral bone and can lead to fibrocartilage repair tissue. Microfracture is indicated for active patients with smaller articular cartilage lesions (<2-3 cm²) and no more than moderate symptoms, or in lower-demand patients with larger lesions (>2-3 cm²) with mild symptoms. Clinical studies have shown that the combination of microfracture and an appropriate postoperative rehabilitation program can reduce symptoms and restore function, with maximum functional improvement 2 to 3 years after the procedure.

The function of articular cartilage is to enable smooth, pain-free gliding of joints during skeletal motion. Articular cartilage is a hypocellular, avascular tissue with a dense collagen and proteoglycan matrix that provides a low-friction, wear-resistant surface. Articular cartilage routinely sustains forces of 1 to 2 megapascals (MPa), but can sustain forces of over 8 MPa.[1] However, despite its durability and intrinsic ability for long-term maintenance, articular cartilage is vulnerable to traumatic injury and degenerative diseases that can lead to irreversible damage. An understanding of the organization of normal articular cartilage, the mechanisms of cartilage injury, and the tissue's limited potential for repair is essential for the effective management of cartilage injuries.

Composition and Organization of Normal Articular Cartilage

Articular cartilage is comprised of a large extracellular cellular matrix that is saturated with water (65%-85% of the total tissue weight). The predominant components of this matrix are type II collagen (75% dry tissue weight) and aggrecan, a complex proteoglycan molecule (20%-25% dry tissue weight). Other matrix proteins include, but are not limited to, fibronectin, oligomeric protein, and thrombospondin. Within this highly organized matrix resides a population of chondrocytes that produce matrix constituents and are generally responsible for cartilage homeostasis.[2]

The ultrastructure of articular cartilage can be divided into zones: a superficial zone, a transitional zone, and a deep zone.[3] Each cartilage zone has a characteristic composition that imparts unique mechanical properties. The superficial zone has a low proteoglycan content and contains densely packed collagen fibers that are parallel to the joint surface. Consequently, the superficial zone has a low fluid permeability and resists shear forces. The transitional zone is characterized by the highest concentration of proteoglycans, making it less stiff than the superficial zone, and an arcade-like structure of collagen fibers. The collagen bundles in the deep zone are oriented perpendicular to the subchondral plate, and the proteoglycan content is lower than in the transitional zone. The chondrocytes are organized in a columnar arrangement and decrease in density from the superficial zone to the deep zone.
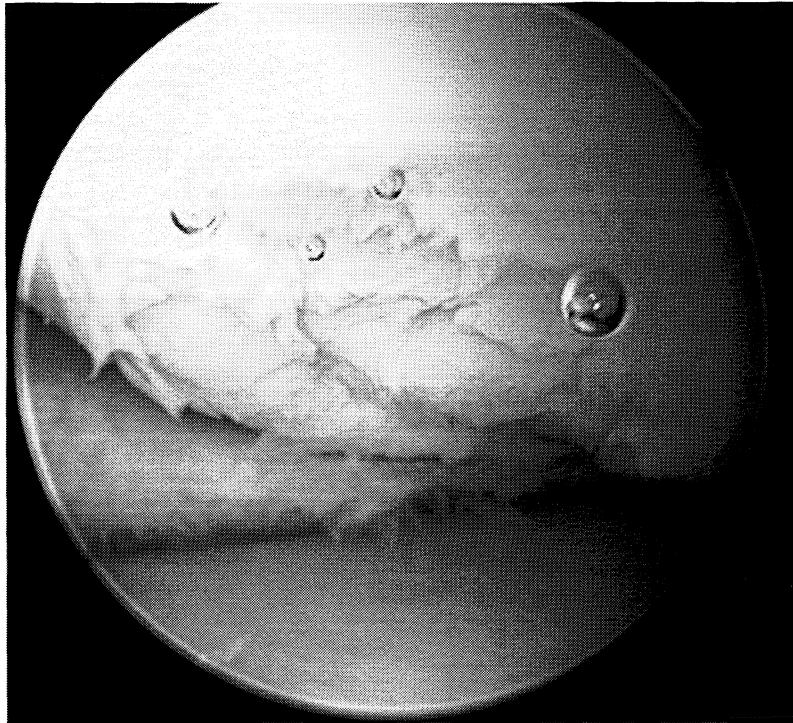
Figure 1. Grade III-IV chondral lesion of medial femoral condyle before preparation for microfracture.

The mechanical response of cartilage to loading is caused by a combination of its ultrastructural organization and its viscoelastic properties.[2] The viscoelastic properties of articular cartilage are the result of 2 phenomenon: interstitial fluid flow (mainly water) through the porous-permeable solid matrix, and the interaction between collagen fibers and molecules of proteoglycan. This viscoelastic behavior contributes to energy dissipation along with load bearing and joint lubrication. Injury to any 1 of the 3 layers of articular cartilage, or to the cells that maintain these layers, can disrupt the biomechanics of the joint lining and may lead to further degeneration and breakdown.

Mechanical Injury and Osteoarthritis

Injury to articular cartilage can be acute, chronic, or acute-on-chronic in nature. Full thickness chondral injuries secondary to work-related or sporting activities occur commonly, accounting for 5% to 10% of pathology after an acute hemarthrosis.[4] Single or repeated impact loading, either secondary to trauma, or owing to malalignment, is the most common cause for cartilage loss. Chronic abnormal loading of a joint surface and the resulting increase in shear forces leads to delamination of the cartilage[5] and irreversible changes in the biochemical composition. Loading studies on articular cartilage in a canine model showed significant increases in water and proteoglycan concentrations that were observed as early as 2 weeks after abnormal loading.[6]

Focal cartilage defects can also result from osteochondritis dissecans. Osteochondritis dissecans is an osteonecrotic lesion of the subchondral bone that may have either a vascular etiology or be the result of repetitive trauma. Collapse of the subchondral bone usually involves the overlying cartilage. Treatment of an osteochondritis dissecans lesion can be different from that of a traumatic focal chondral defect, and is determined by the stage of the osteochondritis dissecans lesion and its healing potential.[7]

Although chondral injuries have not been unequivocally correlated with the development of osteoarthritis, a recent clinical follow-up study found a 50% incidence of radiographic joint space narrowing at an average of 14 years after arthroscopic debridements of a unipolar, uni-
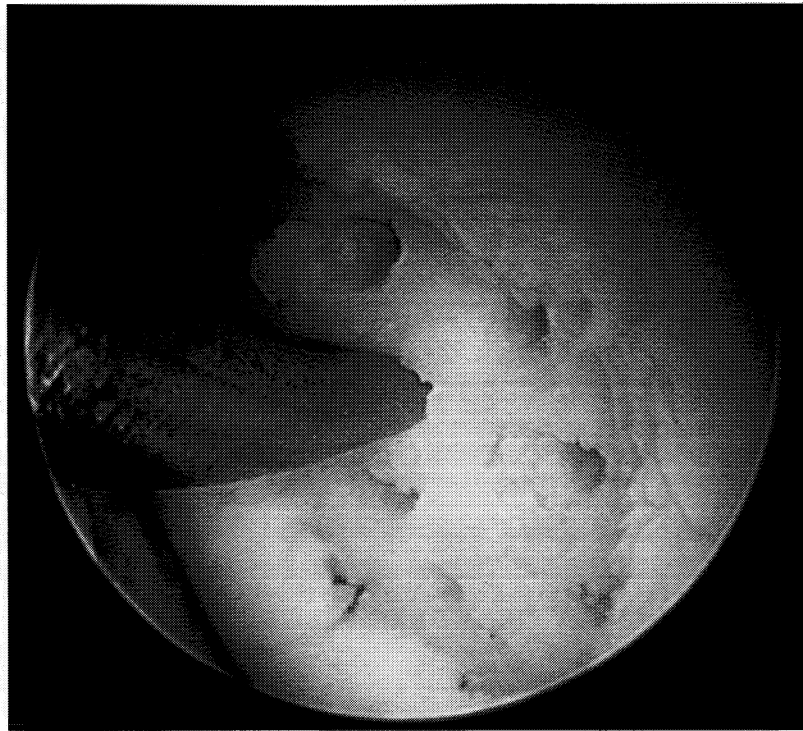
Figure 2. Lesion prepared with vertical walls and debridement of the calcified cartilage layer, showing subchondral penetration with the microfracture awl.

compartmental, full-thickness cartilage lesion.[8] The site of osteoarthritis initiation, whether the cartilage or the bone, is still unknown. Grossly, early osteoarthritis is characterized by fibrillation and fissuring of the articular surface; this progresses to full-thickness cartilage loss with ebernation of the subchondral bone. Histologically, the initial changes occur in the superficial layer of the cartilage in the early stages of osteoarthritis. As the disease progresses, there is a loss of normal staining in the deeper articular zones, a disruption of the tidemark, and an increase in chondrocyte clones, particularly at the surface layers.[9]

Healing of Articular Cartilage Injuries

It has been well documented that, in humans, damaged articular has a limited capacity for repair; this holds true for both partial- and full-thickness lesions.[10] Two main factors contribute to the limited intrinsic repair capacity of articular cartilage: (1) the avascular nature of the tissue, and (2) the relative absence of an undifferentiated cell population that can respond to injury. In addition, articular cartilage is under constant load and thus presents a more challenging mechanical environment for a potential healing response. Intrinsic cartilage repair does not follow the 3 steps that occur after injury to other tissues in the body: necrosis, inflammation, and repair with remodeling. The cells that are mobilized after an injury to the cartilage surface can set up a repair matrix; however, this matrix is morphologically, chemically, and mechanically inferior to the original articular cartilage.

Many of the surgical techniques that have been used in an attempt to treat full-thickness lesions of articular cartilage are designed to stimulate a local influx of undifferentiated mesenchymal cells from the subchondral marrow. These techniques include drilling or microfracture at the base of a cartilage defect; however, these cells produce a fibrocartilaginous reparative tissue that, as mentioned, is biomechanically inferior to the native articular cartilage. Treatment modalities that do not penetrate the subchondral plate, such as local debridement, abrasion arthroplasty, or thermal treatment, are of
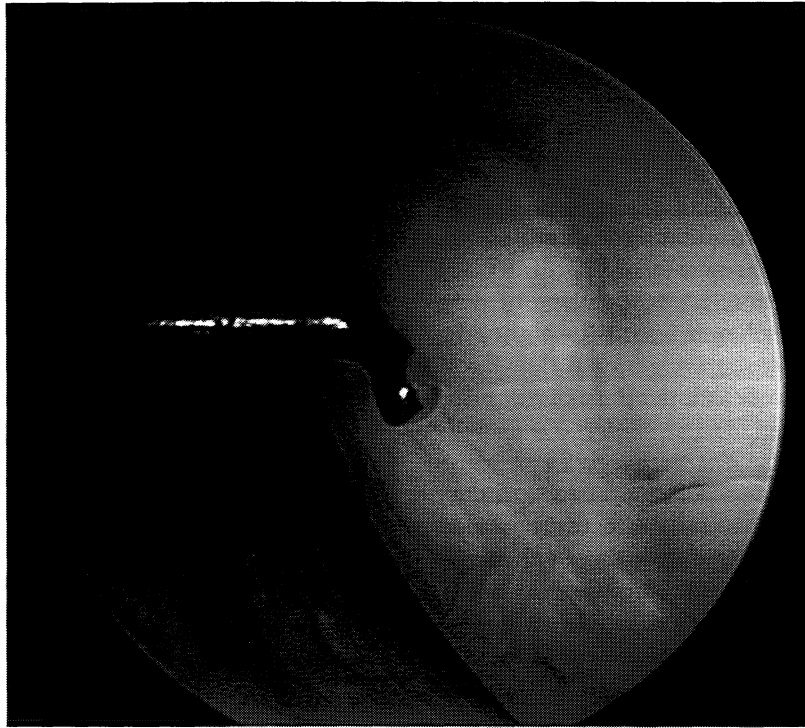
Figure 3. Second-look arthroscopy at 12 months after microfracture, showing fibrocartilage fill of the defect.

questionable efficacy in the treatment of full-thickness defects of cartilage lesions because these modalities will not lead to the recruitment of a large population of undifferentiated mesenchymal cells.

Chondral Injuries of the Knee

Injury to the articular cartilage of the knee is common, accounting for 63% of the lesions found during a review of 31,516 arthroscopies.[11] The natural history of chondral injury is not well defined, but once patients become symptomatic from these lesions, they are likely to progress. Investigators continue to study the relationship between focal cartilage injury and the development of degenerative arthritis. The similar biologic, mechanical, and macroscopic features indicate that both conditions may be part of a continuum of joint deterioration. Both the symptomatic nature of focal chondral lesions and the potential for these lesions to progress provide the rationale for early intervention in symptomatic patients.

Focal chondral defects of the femur comprise a specific subset of articular cartilage injuries.

The Modified International Cartilage Repair Society Chondral Injury Classification System classifies chondral injuries based on the amount and depth of the cartilage lesion, but most commonly, these lesions are classified by the Outerbridge classification (Table 1).[12] Regardless of the class of injury, articular cartilage has limited capacity to heal.[13,14]

The principal goals for surgical management of the symptomatic chondral defect are to reduce symptoms, improve joint congruence by restoring the joint surface, and to prevent additional cartilage deterioration. Based on their anticipated outcome, it is helpful to define treatment options as being palliative, reparative, or

Table 1. Modified Outerbridge Classification for Grading Cartilage Lesions

Grade	Description
I	Softening of the articular cartilage
II	Fibrillation or superficial fissures of the cartilage
III	Deep fissuring of the cartilage without exposed bone
IV	Exposed subchondral bone

restorative.[15] Effective first-line treatment for smaller injuries in lower-demand patients with limited symptoms consists of palliative procedures such as debridement and lavage. Relief, however, may be incomplete and short lived. Midsized lesions in patients with moderate symptoms can be treated with a reparative procedure by using a marrow-stimulating technique (ie, drilling, abrasion arthroplasty, or microfracture) in an effort to promote a fibrocartilage healing response. Results in larger lesions in higher-demand patients, however, are generally less favorable and shorter lived, independent of any prior treatments rendered. Larger defects, especially in higher-demand patients with significant symptoms who have failed less-aggressive primary treatment options, are most effectively treated with a restorative treatment option such as autologous chondrocyte implantation or osteochondral grafting. The focus of this article is on reparative techniques.

Marrow-stimulating techniques include subchondral drilling, abrasion arthroplasty, and microfracture. Abrasion arthroplasty has been used for many years in the treatment of full-thickness articular cartilage lesions, usually in the face of more global osteoarthritis. The procedure was initially popularized by Pridie,[16] who described the procedure of drilling sclerotic bone to obtain fibrocartilage healing in osteoarthritis. Open debridement has provided satisfactory results in 65% of patients at 6.5 years.[17] Arthroscopic abrasion arthroplasty, popularized by Johnson,[18,19] is an arthroscopic modification of the Pridie[16] technique. This technique has provided satisfactory results in several series, including subjective improvement in 78% of patients at greater than 2 years.[18-20] However, other investigators have reported unpredictable results with abrasion arthroplasty, and advocate simple joint debridement.[21,22] The use of abrasion arthroplasty has been limited to the osteoarthritic knee, however, and its use in focal chondral defects of the knee is largely unknown.

The technique of microfracture was developed by Steadman.[23,24] The premise of the microfracture technique is to repair a focal chondral defect with fibrocartilage. Fibrocartilage repair occurs through surgical penetration of the subchondral plate, which exposes the damaged area to progenitor cells that reside within the subchondral bone. The defect forms a scar at 10 days, which becomes less vascular and more sclerotic over time and eventually produces a fibrocartilaginous mass that heals the defect. However, this repair tissue possesses a preponderance of type I collagen rather than type II collagen, rendering it biologically and biomechanically inferior to hyaline cartilage. Studies have shown that fibrocartilage may be unable to function properly in a high-stress environment with load bearing, and may actually lead to further cartilage degeneration and osteoarthritis.[25]

Microfracture is theoretically favored over subchondral drilling and abrasion arthroplasty for several reasons: (1) it is less destructive to the subchondral bone because it creates less thermal injury than drilling; (2) it allows better accesses to difficult areas of the articular surface; (3) microfracture provides a controlled depth penetration; and (4) selection of the correctly angled awl permits the microfracture holes to be made perpendicular to the surface of the subchondral plate.[24,26] Basic science studies have shown histologic evidence that subchondral drilling may result in longer-lived fibrocartilage repair than abrasion arthroplasty in the treatment of full-thickness articular cartilage lesions.[27] In addition, the microfracture technique has been studied in surgically created articular cartilage defects in horses.[28] Microfracture has been shown to increase the tissue volume and the percentage of type II collagen in filling defects when compared with untreated articular cartilage defects.[28] However, there are currently no clinical studies showing the advantage of microfracture to subchondral drilling.

The microfracture technique can be used to treat patients with moderate symptoms and midsized lesions, grade III or IV by the modified Outerbridge classification (Fig 1).[12] Specifically, microfracture is recommended for active patients with smaller lesions (<2 cm^2) and no more than moderate symptoms, or in lower-demand patients with larger lesions (>2 cm^2) and mild symptoms.[29] Results in higher-demand patients with larger lesions are generally less favorable and shorter lived and, in general, microfracture should not be used for defects over 10 mm in depth.[30]

Surgical Technique of Microfracture Treatment

The microfracture technique, as originally described by Steadman et al,[24] begins with a routine, 10-point diagnostic arthroscopy, with a careful examination of the posterior aspects of the medial and lateral femoral condyles. Any surface changes on the articular surfaces is noted, and a probe is used to assess the quality of the cartilage. Next, the focal chondral defect is debrided. An arthroscopic shaver or curette can be used to sharply debride any unstable flaps. A curette should then be used to create vertical walls around the articular cartilage defect and debride the calcified cartilage layer from the base of the lesion (Fig 2). Removal of the calcified cartilage layer greatly enhances the percentage of the defect that is filled, presumably because it provides a better surface for adherence of the clot and improved chondral nutrition through subchondral diffusion.[28] Also, the creation of a perpendicular edge of healthy, viable cartilage around the defect provides an area where the clot of progenitor cells may form and adhere. Additionally, a well shouldered defect provides a discrete load-bearing transition zone. This transition zone then creates an optimal load-sharing environment for the normal surrounding cartilage.

After adequate debridement of the chondral defect, any associated intra-articular disease should be addressed before the microfracture is performed. Then, a surgical awl is used to make multiple small holes in the exposed bone of the chondral defect. These holes should be spaced 3 to 4 mm apart (3-4 holes/cm²). To ensure the integrity of the subchondral plate, the holes should not connect or become confluent. The microfracture holes should be made around the periphery of the defect first, and the brought toward the center of the lesion. Penetration of the most peripheral aspects of the lesion aids healing of the repair tissue to the surrounding articular surface.

After completion of the microfracture, the arthroscopic pump should be turned off, and blood and fat droplets should flow from the area of microfracture. If there is adequate flow of marrow elements, the procedure is complete. Intra-articular drains should not be placed to allow a blood clot rich in marrow elements to form and stabilize while covering the lesion.[24]

Postoperative Rehabilitation After Microfracture

Postoperative rehabilitation plays a vital role in achieving the best results from microfracture.[23,26,31] All patients should use a continuous passive motion (CPM) machine on the day of the surgery and continue it at home for a period of 4 to 6 weeks, 6 to 8 hours per day. Alternatively, full-knee passive range of motion can be performed without a machine with 500 repetitions, 3 times per day.[23,26]

The anatomic location and size of the defect dictates the amount of postoperative weight bearing. Patients with patellar and trochlear groove lesions should be placed immediately in a hinged brace with a 30° to 45° flexion stop for at least 8 weeks. However, patients with these lesions may be allowed weight bearing as tolerated, preferably in extension.[26] The brace protects the lesion because the median ridge of the patella does not engage the trochlear groove until after 30° of flexion. If the microfractured area is in the medial or lateral compartment, the patient is kept strictly touchdown weight bearing (15% weight bearing) for 6 to 8 weeks. If the lesion is in a non–weight-bearing region of the compartment, weight bearing may begin as early as 6 weeks after surgery, depending on the size of the affected areas.

After the period of protected weight bearing, patients begin active range of motion exercises and progress to full weight bearing. No cutting, twisting, or jumping sports are allowed until at least 4 to 6 months after surgery.[24,26]

Clinical Results of Microfracture

The clinical results of microfracture treatment for focal chondral defects are severely limited. Steadman et al[24] have reported that the microfracture procedure has been performed in more than 1,800 patients. However, published clinical results on the patients treated with microfracture are sparse. The first study on long-term results of microfracture was presented at the first annual meeting of the International Cartilage Repair Society.[32,33] A summary of these results was provided by Gill and MacGillivray,[32] al-

though the complete study is not presented. The results of microfracture were reviewed in over 100 patients with full-thickness chondral defect, with an average follow-up evaluation of 6 years. Microfracture resulted in statistically significant reduction in pain, swelling, and all functional parameters studied.[32] The ability to walk 2 miles, descend stairs, perform activities of daily living, do strenuous work, and participate in strenuous work all showed significant improvement. Maximum functional improvement was achieved 2 to 3 years after the procedure.[32,33] There was no statistically significant difference in the outcome of the technique for patellofemoral lesions, medial compartment lesions, and lateral compartment lesions. Larger lesions tended to have more pain at final follow-up evaluation than smaller lesions, though this was not statistically significant. Chondral defects treated within 3 months of the initial injury had significantly less pain and better scores for their activities of daily living than defects treated more than 3 months after injury, regardless of lesion size.[32]

Gill and MacGillivray[32] reviewed the results of microfracture for isolated chondral defects (mean size 3.2 cm²) of the medial femoral condyle at The Hospital for Special Surgery. A summary of the results was presented in the article by Gill and MacGillivray,[32] although the complete study data was not provided. The study included 19 patients at a mean follow-up time of 3 years. The calcified cartilage layer was not routinely debrided, and patients did not routinely use CPM or limited weight bearing for 6 weeks. The study used a modified Cincinnati questionnaire to rate the patient's condition. Seventy-four percent of their patients reported minimal or no pain and 63% rated their overall condition as good or excellent. In addition, magnetic resonance imaging was performed on all patients after surgery. Despite the good subjective results, only 42% of the patients had 67% to 100% fill of the defect on magnetic resonance imaging, 21% had 31% to 66% fill, and the remaining 37% only had 0% to 30% fill.[32] There was no correlation found between the size of the defect and the percent of defect fill. Four patients had a smooth transition at the fibrocartilage–articular cartilage interface, whereas the other 15 had a fissure.

An additional study was performed that evaluated the microfracture technique by second-look arthroscopy.[23] Subjectively, Rodrigo et al[23] graded articular cartilage lesions both before and after microfracture technique as grade 1 through 5, with grade 1 representing normal articular cartilage, and grade 5 representing chronic full-thickness articular cartilage loss. The study found a mean subjective improvement in grading of articular cartilage lesions of 2.67 in the CPM group, and 1.67 in the non-CPM group.[23] They concluded that CPM was beneficial in the treatment of articular cartilage lesions by microfracture. However, there were no clinical outcomes reported in the study, and, thus, there is limited ability to correlate the improvement in arthroscopic grading with improvement in patient symptoms after microfracture.

Complications of microfracture are rare, and mimic those seen after arthroscopic debridement and lavage. Occasionally, if a steep perpendicular rim is made in the trochlear groove during preparation of the cartilage defect, patients may experience catching or locking as the apex of the patella rides over this lesion.[26] These symptoms generally dissipate within 3 months. In addition, a recurrent painless effusion can develop between 6 and 8 weeks after microfracture, and can be treated conservatively.[26] Progressive cartilage degeneration and recurrent symptoms are the most common complications, and close postoperative monitoring of patients is required.

Conclusion

Symptomatic focal chondral defects of the articular surface of the knee are a complex clinical problem because of the inability of articular cartilage to initiate a healing response. When used as indicated, the combination of microfracture and an appropriate postoperative rehabilitation program has been shown to reduce symptoms and restore function (Fig 3). Microfracture is the preferred reparative method because it creates less thermal injury than drilling, accesses difficult areas of the articular surface, and provides a controlled depth penetration. Complications are rare and mimic those seen after arthroscopic debridement and lavage, and microfracture does not limit the availability of any future restorative cartilage procedure if it fails. However, there are severely limited clinical results on the

use of microfracture in practice, and the longevity of fibrocartilage repair to provide adequate functional results remains unknown.

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