distraction added to subchondral drilling is effective for repairing an osteochondral defect in contrast to drilling alone in an animal model. In addition, they determined that distraction for 4 weeks was not of sufficient duration for repair of the defect whereas distraction for 8–12 weeks resulted in a good outcome. They also hypothesized that differentiation of mesenchymal progenitor cells from the bone marrow may be promoted by appropriate shearing and compression stresses acting through the joint fluid exerted by joint motion and loading without excessive compression.

Valburg et al. [18] also in a study of OA of the canine knee joint found that joint distraction with motion via an external fixator resulted in a significant improvement in cartilage metabolism.

Therefore, to minimize damage to the repaired tissue, long-term unloading and joint motion with continuous passive motion was applied in this case with a large osteochondral defect in the weight-bearing area of the knee after reconstruction of the bony defect using a combination of autograft and artificial bone.

Articulated joint distraction affords widening of the joint space and reduction of pressure on the regenerating fibrocartilage during weight bearing. Meanwhile allowing functional joint movement, which is one of the most important factors contributing to repair in hyaline-like cartilage [11].

A new articulated distraction devise was used in a previous clinical study by Deie et al. [11]. This new articulated distraction arthroplasty device was developed for the human knee joint and allowed the joint to be smoothly exercised through the functional range of motion during fixation. In accordance with the fact that knee motion is one of the most important factors contributing to repair in hyaline-like cartilage [11].

This device allowed widening of the joint spaces and the continuation of ROM exercises, at the same time, reduction of pressure on the regenerating fibrocartilage during weight bearing, This devise was specially designed not to damage intra-articular structures such as the anterior cruciate ligament, posterior cruciate ligament, and cartilage, with no pin being inserted at the femoral center of knee motion In contrast, in the animal model used by Kajiwara et al. [4], a Kirschner wire was inserted at the femoral center of knee motion to allow full range of motion with articular distraction [4, 11].

An alternative method of treatment of large osteochondral defects is the use of tissue-engineered osteochondral composites. Ochi et al. [24, 25] introduced a new concept for the transplantation of tissue-engineered cartilage, which was made ex vivo by the tissue-engineering technique for the treatment of osteochondral defects of the knee, and demonstrated successful results [23–29].

However, the use of tissue-engineered osteochondral composites require extensive lab work, and has not yet been applied in clinical practice for reconstruction of a large osteochondral defect in the weight-bearing area of human joints. Mosaicplasty, autologous osteochondral grafting, can be used for biological resurfacing of focal osteochondral defects; however, in this technique, the limited amount of autologous tissue and donor site morbidity, as well as the congruency of the reconstructed articular surface are major problems, Tissue-engineered osteochondral composites theoretically have the potential to overcome the limitations associated with autologous osteochondral mosaicplasty [30, 31].

The use of articulated distraction arthroplasty device in this case stimulated biological resurfacing of the reconstructed bony defect with hyaline-like cartilage. This approach constitutes a feasible, easily applied method for the repair of the large osteochondral defect allowing resumption of a functional knee joint. However, the long-term durability, and the biomechanical sufficiency of the reconstructed articular surface is not guaranteed to stand the test of time, and the patient may in the future require arthroplasty.

Conclusion

We experienced a case of large posttraumatic osteochondral defect of the knee joint treated with a novel distraction arthroplasty (DA) device combined with reconstruction of the bony defect using both autologous and artificial bone graft substitute resulting in satisfactory short- and mid-term result, with a painless, stable knee joint with a good functional range of motion.

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Knee Articulated Distraction Arthroplasty for the Middle-aged Osteoarthritic Knee Joint

Masataka Deie, MD, Mitsuo Ochi, MD,† Atsuo Nakamae, MD,† Nobuo Adachi, MD,† Tomoyuki Nakasa, MD,† Takuya Niimoto, MD,† Mohamed Mahmoud Abouheif, MD,† and Wirat Kongcharoensombat, MD†*

Objective: We developed a knee distraction arthroplasty device that allows continuous joint movement. The objective of this article is to show the surgical procedure of knee distraction arthroplasty with a bone marrow-stimulating technique, for treatment of osteoarthritis of the knee and to evaluate the clinical results.

Methods: As we showed in Arthroscopy in 2007, we performed this distraction arthroplasty to 6 knees (in 6 patients, aged 42 to 63 y). Then we compared preoperative findings with postoperative ones. The fixation period for the distraction device ranged from 7 to 12 weeks and the follow-up period ranged from 24 months to 53 months (average 36 mo).

Results: The Japan Orthopaedic Association knee score, range of motion, and the values of the joint spaces were significantly improved in all cases at the latest follow-up ($P<0.05$). Visual analog pain scales were also significantly improved ($P<0.05$).

Conclusions: We conclude that treatment using this arthroplasty device in combination with a bone marrow stimulating method is effective for osteoarthritic knees in middle-aged patients.

Key Words: middle-aged osteoarthritic knee, distraction arthroplasty, articulated distraction device

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Osteoarthritis (OA) of the knee joint is a very prevalent degenerative joint disorder.[1,2] Recent strategies for relatively wide cartilage damage, high tibial osteotomy, or unicomponent knee arthroplasty have been the usual treatments for significantcartilage damage that is limited to one compartment of the knee joint. For older patients, when the osteoarthritic defect has spread over more than 1 compartment of the knee, thus becoming severe, total knee arthroplasty is the appropriate treatment.[3] However, in middle-aged patients, the indications for total knee arthroplasty and unicompartment arthroplasty need to be carefully considered, because of the risk of infection and the limited life span of implants. For this reason, bone marrow-stimulating techniques, which involve drilling and microfracture of the lesions, have become widely accepted for knees with diffuse OA.[4,5] However, there has been some controversy about the clinical outcomes of these procedures.[6–9] The fragile repair tissue induced from the bone marrow may be vulnerable to damage by overloading, whereas reduction of overloading promotes cartilage regeneration. These ideas are supported by findings that new cartilage tissue is formed in the medial tibiofemoral joint after high tibial osteotomy, where overload to the medial condyle has been reduced.[10,11]

Distraction arthroplasty is a technique that has been used mostly at the elbow, hip, and ankle joints to preserve joint space and decrease the weight-bearing load. It delays the need for arthrodesis or joint replacement surgery.[12–14] Ideally, allowance should be made for continuous joint movement, because movement is essential for cartilage repair.[15,16] For this reason, Ochi, who was senior author, developed an articulated arthroplasty device for the knee joint (MEIRA Co, Nagoya, Japan). In addition to the merits of previous devices, which include preservation of the joint surface and protection against overload of the regenerating fibrocartilage during weight bearing, this articulated device permits smooth exercising of the joint during fixation. Before this clinical study, success of a similar device for treating cartilage damage in an animal model was published.[17] Furthermore, we produced a preliminary report of the clinical results of this knee device in 2007.[18] In this report, we show our detailed surgical procedure involved in distraction arthroplasty.

DISTRACTION ARTHROPLASTY

Preparation Before Surgery

All patients were hospitalized. The distraction arthroplasty was performed under lumbar anesthesia or general anesthesia. Before surgery, the patients' physical findings were

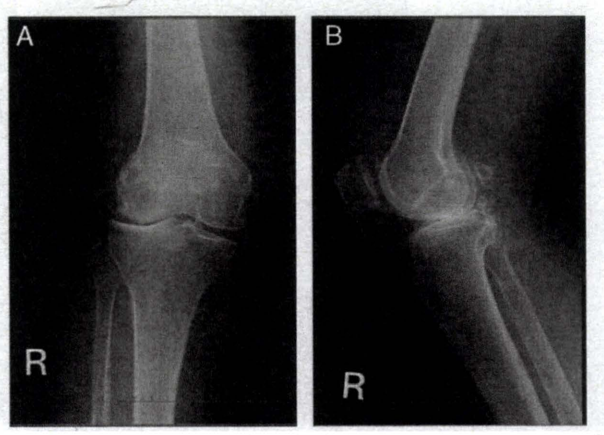

FIGURE 1. A 59-year-old female: (A) anteroposterior view and (B) lateral view.

From the *Department of Physical therapy and Occupational therapy, Graduate School of Health Sciences; and †Department of Orthopaedic Surgery, Graduate School of Biomedical Science, Hiroshima University, Hiroshima, Japan.
No potential conflict of interest declared.
Address correspondence and reprint requests to Masataka Deie, MD, Department of Physical therapy and Occupational therapy, Graduate School of Health Sciences, Hiroshima University, 1-2-3 Kasumi, Minami-ku, Hiroshima 734-8553, Japan. E-mail: snm3@hiroshima-u.ac.jp.

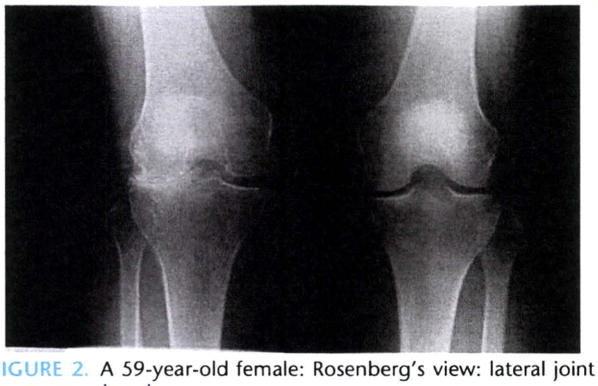

FIGURE 2. A 59-year-old female: Rosenberg's view: lateral joint space was closed.

examined: anterior-posterior view x-ray, lateral view x-ray (Figs. 1A, B), Ronsenberg view x-ray[19] (Fig. 2), and magnetic resonance imaging (Figs. 3A, B).

SURGICAL PROCEDURE

Bone Marrow Stimulation Under Arthroscopy

Arthroscopy was used to examine the cartilage surfaces, menisci, and ligaments in all of the cases. For arthroscopy, we used infrapatellar medial and lateral portals, and a pump inflow pressure of 80 mm Hg/m. When meniscal tears were found, we additionally performed partial menisectomy of the menisci. Bone marrow stimulation was then performed under arthroscopy. The OA lesions were drilled with 1.5-mm Kirschner wire or microfractured with an ice pick at 4 to 5 points/cm^2 (Fig. 4).

Fixation of Distraction Arthroplasty Device

After drilling and microfracture, the external device was fixed. At the proximal tibia, the 2-mm guide pin was passed parallel with the joint line. The position was checked using fluoroscopy (Fig. 5), and two 6-mm pins were drilled into the proximal tibia at 2 cm below the tibial plateau surface (Fig. 6) to fix the external device. These pins indicated the optimum location of the external fixation device. Next, two 2-mm guide pins were inserted into the apexes of the medial and lateral epicondyles, which are at the center of rotational motion of the knee. These guide pins did not penetrate the intercondylar space and did not damage the intra-articular ligaments. Then, according to the original guide frame (Fig. 7A), 2-mm guide pins were inserted, followed by two 6-mm pins, which were passed through the femur bone (Fig. 7B). The external device was fixed and the distractive tension applied (Fig. 8). We checked the range of motion (ROM) (Figs. 9A, B) and used arthroscopy to determine how much to increase the tibio-femoral joint space. The postdistraction and predistraction tibio-femoral joint spaces were measured using the length of a probe, with the knee at 10 degrees of flexion and without any valgus or varus stress. Finally, we examined the x-ray to check the change in the joint space (Fig. 10).

Postoperative Rehabilitation

A soft knee brace was fixed for 2 weeks. Continuous passive motion exercise commenced 2 weeks after the external device was fixed, and was continued for approximately 2 weeks. Patients were allowed to walk with partial weight bearing from 3 weeks after surgery. One month after surgery, patients were allowed to walk with full weight bearing.

Removal of the Device and Follow-up Arthroscopy

The external fixation device was removed 2 to 3 months after fixation. After the external device was removed, follow-up arthroscopy was performed in all cases to observe the articular surface that had been treated by the bone marrow stimulation procedure.

CLINICAL RESULTS

The detailed clinical results were shown our earlier report in 2007.[18] From April 2002 to September 2005, we performed this distraction arthroplasty and bone marrow-stimulating method on 7 knees (in 7 patients). In these knees, the OA had spread to both medial and lateral tibio-femoral joints. The indication for the procedure was grade 3 or greater using the Kellgren-Lawrence classification, at 1 or 2 compartments of the tibio-femoral joint. All of the patients provided consent for treatment with this therapy. One patient was excluded from the analysis, because he was found to have rheumatoid arthritis after the surgery. The remaining subjects comprised 2 men and 4 women, aged 42 to 63 years (mean: 49 y). According to the Kellgren-Lawrence grading scale, 1 case was grade 3 and

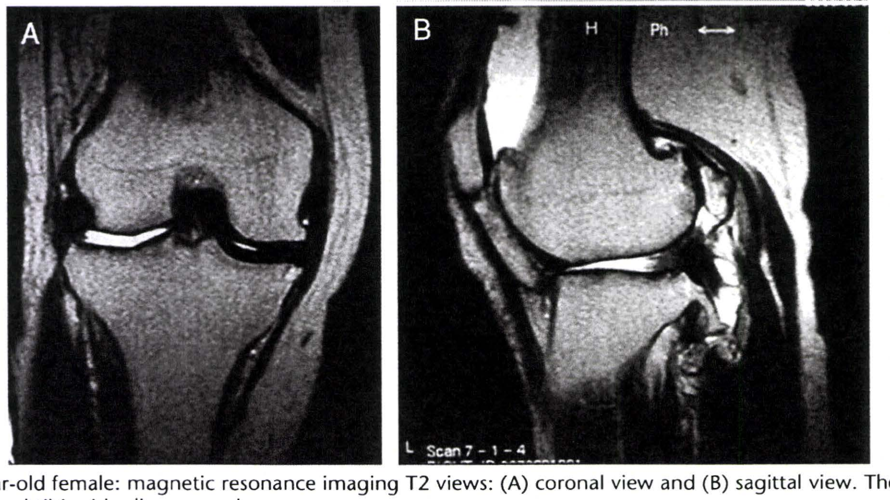

FIGURE 3. A 59-year-old female: magnetic resonance imaging T2 views: (A) coronal view and (B) sagittal view. The articular cartilage on both the femur and tibia side disappeared.

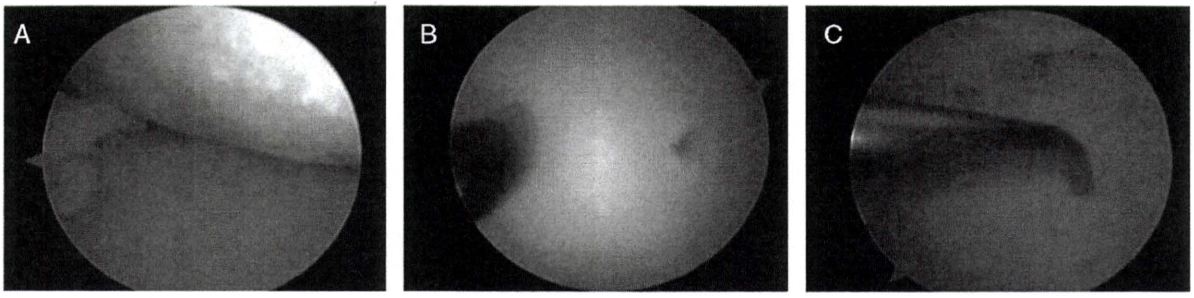
FIGURE 4. Arthroscopic view of lateral compartment of tibio-femoral joint (A). B, Microfracture performed on the femoral condyle. C, Microfracture performed on the tibial plateau.

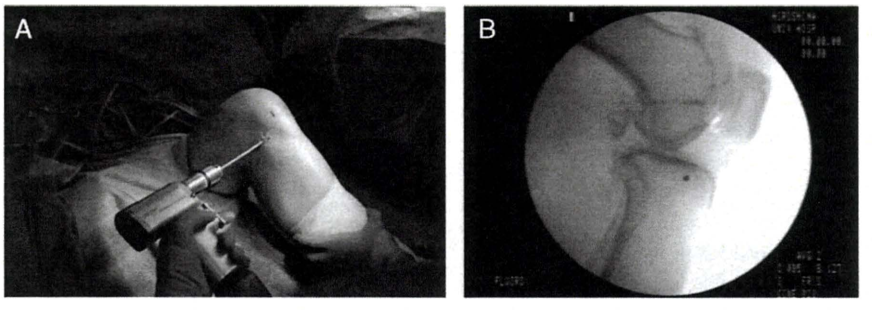
FIGURE 5. Before passing the 6 mm pins, we checked the position of the insertion site using 2 mm guide pins (A) with fluoroscopy (B).

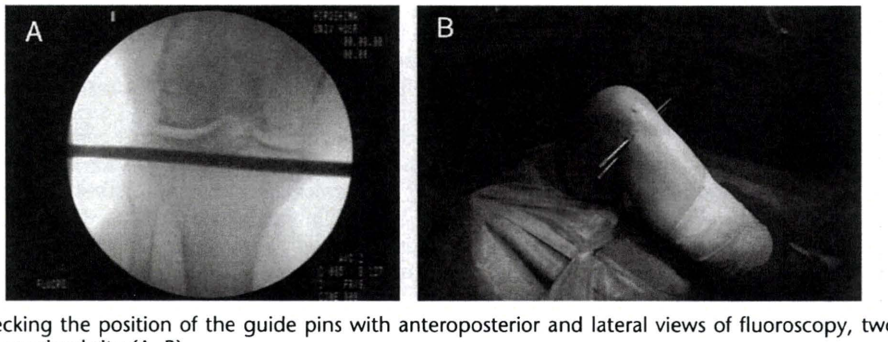
FIGURE 6. After checking the position of the guide pins with anteroposterior and lateral views of fluoroscopy, two 6 mm pins were inserted at the tibial proximal site (A, B).

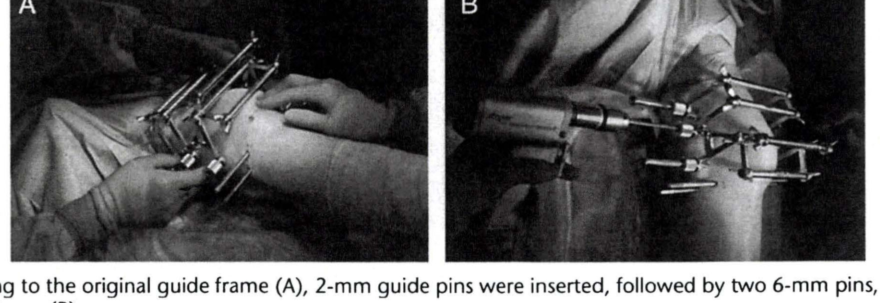
FIGURE 7. According to the original guide frame (A), 2-mm guide pins were inserted, followed by two 6-mm pins, which were passed through the femur bone (B).

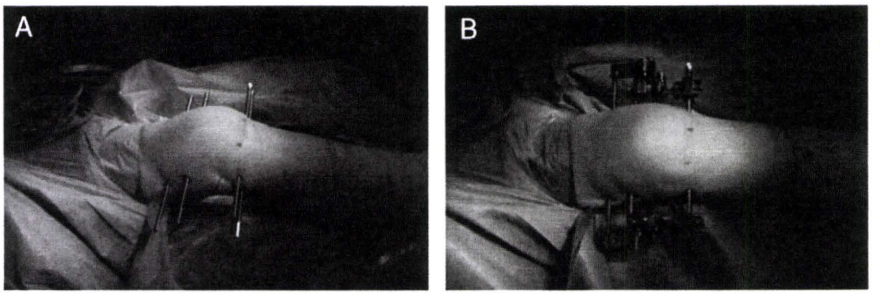

FIGURE 8. The two 6 mm pins were inserted into the femur bone (A), then the external device was fixed and the distractive tension applied (B).

5 cases were grade 4. The fixation period of the distraction device ranged from 7 to 13 weeks (mean: 9 wk). The follow-up period ranged from 2 to 4 years and 5 months (mean: 3 y).

COMPLICATIONS

Although 2 cases had suffered a superficial skin infection around the insertion of the pin at the tibia and the femur, none had experienced any major complications such as nerve palsy or deep infection.

EVALUATION

We compared preoperative and postoperative assessments of the Japan Orthopaedic Association score, the ROM, the joint space by the Rosenberg x-ray view,[19] and the visual analog pain scale. The Rosenberg x-ray view was carefully taken as a posteroanterior view. The patient stood with the knees flexed to 45 degrees, and with the anterior aspect of the knee touching the radiographic cassette. The x-ray beam was centered at the joint line, parallel to the tibial plateau.[19] The narrowest joint space on the preoperative and postoperative Rosenberg x-ray views was measured for every patient by one of the co-authors. Preoperative and postoperative data were analyzed using the paired t test. P value less than 0.05 was considered significant.

RESULTS

After the external devices were removed, the follow-up arthroscopies revealed that in all cases the regions treated with the bone marrow-stimulation procedure were covered with newly formed tissues.

The Japan Orthopaedic Association score significantly improved from a mean of 56 points (range: 55 to 60 points) before treatment to a mean of 81 points (range: 70 to 85 points) after treatment ($P<0.001$). The ROM (mean ± SD) was -5 ± 4 to 111 ± 5 degrees before surgery. During the external fixation, the ROM decreased, but at the final follow-up, the mean ROM increased to become -5 ± 3 to 122 ± 5 degrees. The joint space, as measured by the Rosenberg x-ray view, increased from a preoperative mean of 0.4 mm (range: 0 to 1.0 mm) to a mean of 1.6 mm (range: 0 to 3.0 mm) at external fixation. At the final follow-up, the joint space remained at a mean of 1.6 mm (range: 0 to 3.0 mm). Visual analog pain scales significantly improved from a mean of 9 points (range: 8 to 10 points) before treatment to a mean of 4 points (range: 1 to 7 points) ($P=0.001$).

DISCUSSION

We have been performing the articulated distraction arthroplasty procedure since 2002, and we reported a preliminary clinical result in 2007.[18] We used an articulated distraction arthroplasty device that was developed for the human knee joint by Ochi, and that allowed the joint to be smoothly exercised during fixation. This device allowed widening of the joint spaces and the continuation of ROM exercises. It was specially designed not to damage intra-articular structures such as the anterior cruciate ligament, the posterior cruciate ligament, and cartilage, with no pin being inserted at the femoral center of knee motion. Another feature of our procedure was that distraction of the joint space elongated the contractured ligaments of the knee joint. In this study, we found not only enlargement of the joint space and improvement of pain, but also an increase in the ROM. From these findings, we expect joint contracture to be reduced even after the patient's external fixation device is removed.

Former distraction arthroplasty procedures satisfied only 2 factors in the repair of a damaged joint surface: (1) widening of the joint space and (2) reduction of pressure on the regenerating fibrocartilage during weight bearing.[13,14] These procedures did not enable functional joint movement, even though knee motion is one of the most important factors contributing to repair in hyaline-like cartilage. In one clinical study, a hinge-distractor apparatus was used to provide some movement of the knee and elbow joint, but it did not allow continuous active movement.[20]

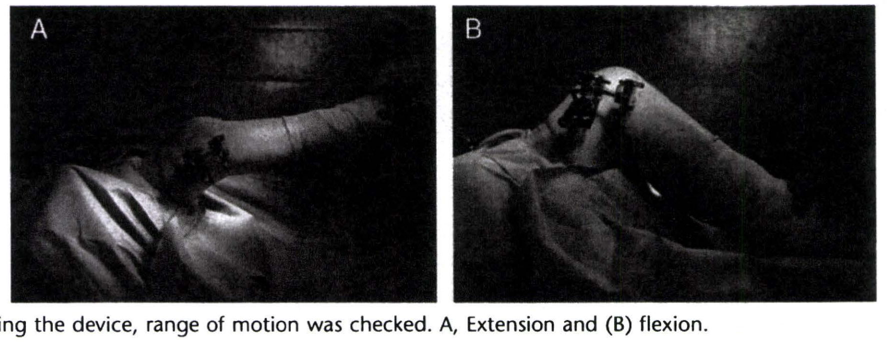

FIGURE 9. After fixing the device, range of motion was checked. A, Extension and (B) flexion.

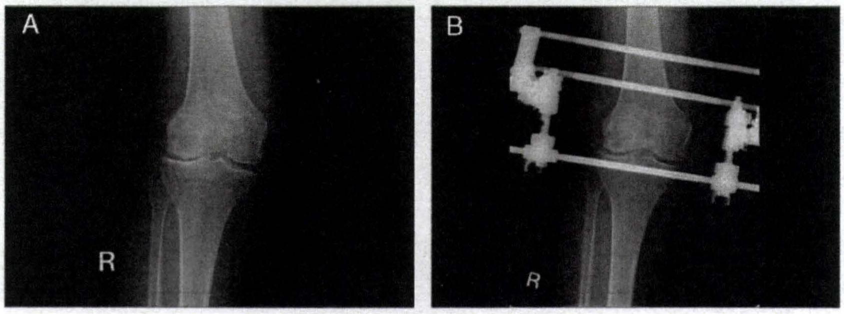

FIGURE 10. After distraction, the joint space was wider (B) than before surgery (A).

In an animal model, Kajiwara et al[17] evaluated damaged rabbit knees treated with an articulated distraction arthroplasty device or with the drilling method. They described that the distraction device in combination with subchondral drilling was more effective for repairing an osteochondral defect than drilling alone. Furthermore, they determined that distraction for 4 weeks was not of sufficient duration for repair of the defect, whereas distraction for between 8 and 12 weeks resulted in a good outcome.

We believe that good clinical results were achieved because the device enhanced joint space and joint movement. This would have favored the unloading and protection from damage of the newly formed fibrocartilage that was produced after bone marrow stimulation.

However, it is necessary to continue the clinical and basic studies to resolve some uncertainties of this arthroplasty. Firstly, the appropriate distraction force and the optimal loading are still unclear. The measurement of load pressure in the joint of a living human is difficult. Therefore, we checked the joint space after fixing the device and compared the postfixation and prefixation spaces using arthroscopy and Rosenberg x-ray views. Secondly, it was necessary to estimate the appropriate fixation period. We removed the articulated distraction device after 7 to 12 weeks. There were 2 reasons for choosing this duration of fixation: (1) the patients' lifestyles were restricted by the device, and (2) we took into account the findings of Kajiwara et al,[17] that distraction for 8 to 12 weeks results in a good outcome. Thirdly, the number of cases included in this study was small, and the follow-up period was limited.

In conclusion, we described that the distraction arthroplasty using the knee distraction arthroplasty device is effective for OA of middle-aged knees.

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3T-MRI における関節軟骨変性の定性的、定量的評価
－病理組織像との比較

久保晴司 [1)]、黒田良祐 [1)]、岩間祐基 [2)]、松下雄彦 [1)]、松本知之 [1)]、藤井雅彦 [2)]、杉村和朗 [2)]、黒坂昌弘 [1)]

3T-MRI では、高い signal noise ratio(SNR)を活用することで軟骨病変のより詳細な評価が可能となり、関節変性疾患に対する応用が期待されている。本研究の目的は、3T-MRI の画像所見が関節軟骨の病理所見をどの程度まで反映しているのかを定量的に評価することである。関節軟骨の定量的な評価に有用な MRI 撮影法として dGEMRIC、T1roh, T2 mapping が諸家により報告されているが [1)-3)]、本研究では、コントラストに優れた脂肪抑制プロトン強調像(FS-PDWI)を用いてまず定性的性評価を行い、造影剤を使用すること無く、比較的簡便に撮影できる T2 mapping による T2 値を用いて関節軟骨変性の定量的評価を行った。

【対象と方法】

対象は内反型変形性膝関節症に対し全人工膝関節置換術を行った 10 例（女性 9 例、男性 1 例、年齢 58 から 78 才、平均年齢 71 才）の大腿骨外顆荷重面である。まず術前に、3T-MRI(Philips 社製 Achiva 3T)を用いて、矢状断での脂肪抑制Ｔ２強調像、T2 mapping, 脂肪抑制プロトン密度強調像を撮影した。次いで、病理学的評価として、手術にて切除した大腿骨外顆を脱灰病理標本とし、HE 染色、safraninO 染色した。まずＨＥ染色で形態の評価を行い、サフラニンO染色で、関節軟骨の変性、軟骨基質の染色性の低下などを評価した。定性的な検討項目として MRI 所見と、病理のマクロ像がどの程度一致しているか、関節軟骨の全層欠損、軟骨の層構造の一部破壊、広範な軟骨の変性菲薄化、につきに評価した。軟骨変性の定量的評価としてはそれぞれの標本で 4 カ所の region of interest(ROI)を設定し、その染色性を 3 段階（normal, moderate, poor）に grading し、各 grade における ROI の術前矢状断 MRI（1．脂肪抑制プロトン密度強調画像：FS-PDWI, 2．T2 mapping）各撮像法での信号強度を比較した。

【結果】定性的評価においては、軟骨全層欠損、軟骨の層構造の一部破壊ないし軟骨表面のみの変性、関節軟骨の変性と菲薄化いずれについても FS-PDWI において優れたコントラストを示し、形態的評価においても有用であった（図 1)。

Quantitive evaluation of degenerative change of articular cartilage using 3T-MRI

: Seiji Kubo et al. (Department of Orthpaedic Surgery, Kobe University Graduate School of Medicine)

1) 神戸大学整形外科、2) 神戸大学放射線科

Key Words: articular cartilage, MRI, histology

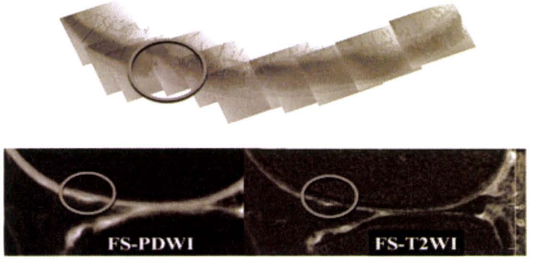

図１．肉眼的には軟骨の層構造の一部破壊もFS-PDWIにおいてより鮮明に描出されている

一方、safraninO染色性のgradeによる定量的評価においてはFS-PDWI信号強度はnormal群(1349±244), moderate群(1386±292) poor群(1528±199)といずれの群間にも信号強度に有意差を認めなかったのに対し、T2 mappingによるT2値ではnormal群（42.1±6.4）, moderate群（47.1±10.1）,poor群(69.7±14.6)であり、safraninO染色性normal群はsafraninO染色性poor群に比べ有意に低いT2値を示していた。(p<0.05)。moderate群では他の群との統計学的有意差を認めなかった（図２）。

【考察】

FS-PDWIでは関節軟骨と軟骨下骨、半月板のコントラストが明瞭で関節軟骨の全体像や形態をとらえるにはもっとも適していると考えられたが、定量的評価においてはsafraninO染色性によって信号強度に有意な差が無かった。一方、T2 mappingでは形態的評価におけるコントラストには劣るものの、高度軟骨変性によってT2値は有意に延長し、軟骨変性の定量的評価に適していることが示された。今後、関節軟骨への様々な治療に対する評価にも有用である可能性が示唆された。

結論として、3T-MRIによる脂肪抑制プロトン強調像とT2 mapping撮影法の組み合わせは変性軟骨の定性的、定量的評価に有用であると考えられた

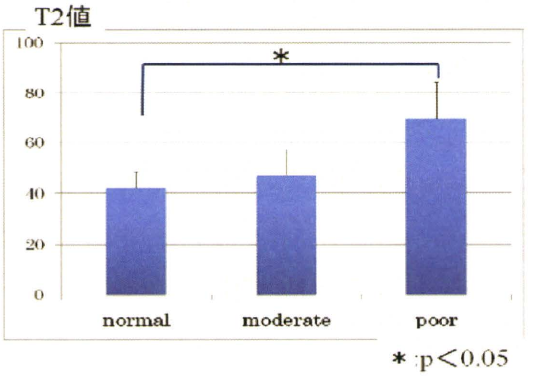

図２．safraninO染色性の違いによるT2値の変化

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MRIによる関節軟骨の画像診断の新たな展開

渡辺淳也[1]　吉岡　大[2]

核磁気共鳴撮像(magnetic resonance imaging；MRI)は関節軟骨の直接的な評価が可能であり，軟骨の損傷や変性の診断にきわめて有用な非侵襲的評価法である。近年，3T MRIの普及や，RFコイル，パルスシーケンスの改良などに伴い，より高い空間分解能での撮像が可能となってきた。また関節軟骨中の分子構造変化を鋭敏に捉えることが可能な新しいMRI撮像法が臨床応用されつつあり，従来困難であった変形性関節症(OA)の早期診断に有用な方法として期待される。本稿では，これらの最新のMRI撮像法などについて解説する。

3T MRIを用いた関節軟骨のルーチンMRI撮像法

3T MRIでは1.5T MRIと比較し，RFコイルなどを含めた撮像条件が同一であれば理論上2倍の信号雑音比(signal to noise ratio；SNR)が得られる[1]。SNRの向上は，空間分解能の向上や撮像時間の短縮に有効であり，骨軟部領域の撮像においても静磁場強度の上昇による多くの恩恵を受けることが可能となる。特に病変が比較的小さく，また薄く複雑な立体構造をとる関節軟骨では，SNRの向上が診断精度に大きく寄与するため，3T MRIを用いたイメージングはきわめて有用性が高い(**図1**)。一方，3T MRIでは1.5T MRIと比較し，緩和時間，磁化率効果，化学シフト効果などが異なるため，撮像プロトコルの作成にあたってはパラメータの設定に注意が必要である。また静磁場強度の上昇に伴う比吸収率(specific absorption rate；SAR)の上昇や磁場不均一性の増加など解決すべき問題も多く存在する。

われわれは3T MRIを用いた関節軟骨や半月板，靱帯などを主な対象としたルーチン撮像では，fast spin echo(FSE)法を用いた少し長めのエコー時間(echo time；TE)のプロトン密度(proton density；PD)強調像("intermediate weighted image"ともよばれる)を中心に用いている(**図2**)。PD強調像では，T1強調像とT2強調像の中間的な像が得られ，軟骨と関節液，軟骨下骨との間に比較的良好なコントラストが得られる。また脂肪抑制法を用いたPD強調像では，関節液は強い高信号に，正常海綿骨は低信号に描出されるため，損傷軟骨部にある関節液や，剥離した骨軟骨片と骨髄との間に介在する関節液を鋭敏に捉えることが可能であり，軟骨損傷の評価に有用である。また比較的短いバンド幅や大きなピクセルサイズを用いた撮像では，化学シフトアーチファクトによる骨髄脂肪像の軟骨像への重なりにより，軟骨の評価が困難となることがあるが，脂肪抑制法を併用すると骨髄脂肪像を抑制することが可能である。

3D isotropic MRI

膝関節のMRIの撮像には，現在さまざまな3Dシーケンスが使われているが，そのほとんどはanisotorpic(非等方性または異方性)なボクセルでの撮像法であり，オリジナルの撮像断面，例えば矢状断から冠状断または横断へのリフォーマット

1. Watanabe A：帝京大学ちば総合医療センター整形外科
2. Yoshioka H：Department of Radiological Sciences University of California, Irvine

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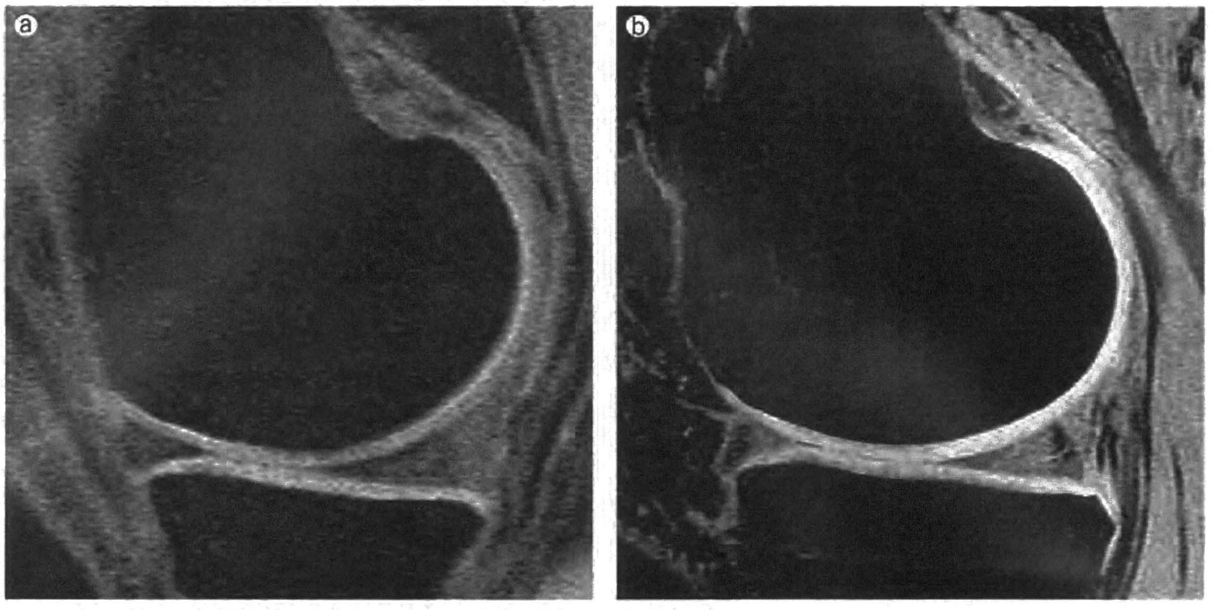
図1 1.5Tと3.0T MRIによる膝関節軟骨描出能の比較



a：1.5T脂肪抑制PD強調矢状断像，b：3.0T脂肪抑制PD強調矢状断像

像は，画像の劣化により診断には役に立たない場合が多い。

それを解決する方法として，3D isotropic(等方性)MRIが近年試みられている。通常の膝関節MRIは，FOV：14～16cm，マトリックスサイズが最低でも256×256以上で撮像すると仮定すると，撮像面内のピクセルサイズは最大でも0.625mmということになり，スライス厚を同じく0.625mmに設定しなければisotropicな画像にはならない。オリジナルの撮像断面を矢状断とし，撮像に必要な膝の左右の幅が12.5cmとするとちょうどスライス枚数は200枚となる。スライス枚数だけでも膨大な数であるが，0.625mmのスライス厚で十分なSNRが得られるかどうか，十分なSNRのためには撮像時間がどのくらい必要なのかなどが実際に臨床応用するには問題となる。

SNRを稼ぐ手っ取り早い方法は，3Tなどの高磁場MRIを用い，マルチチャンネルの膝コイルを使うことである。しかし，十分なSNRの画像が得られても，関節軟骨とその周囲の良好なコントラストが得られる撮像シーケンス(TR，TE，FAなど)を使わなければ軟骨病変の診断はできない。

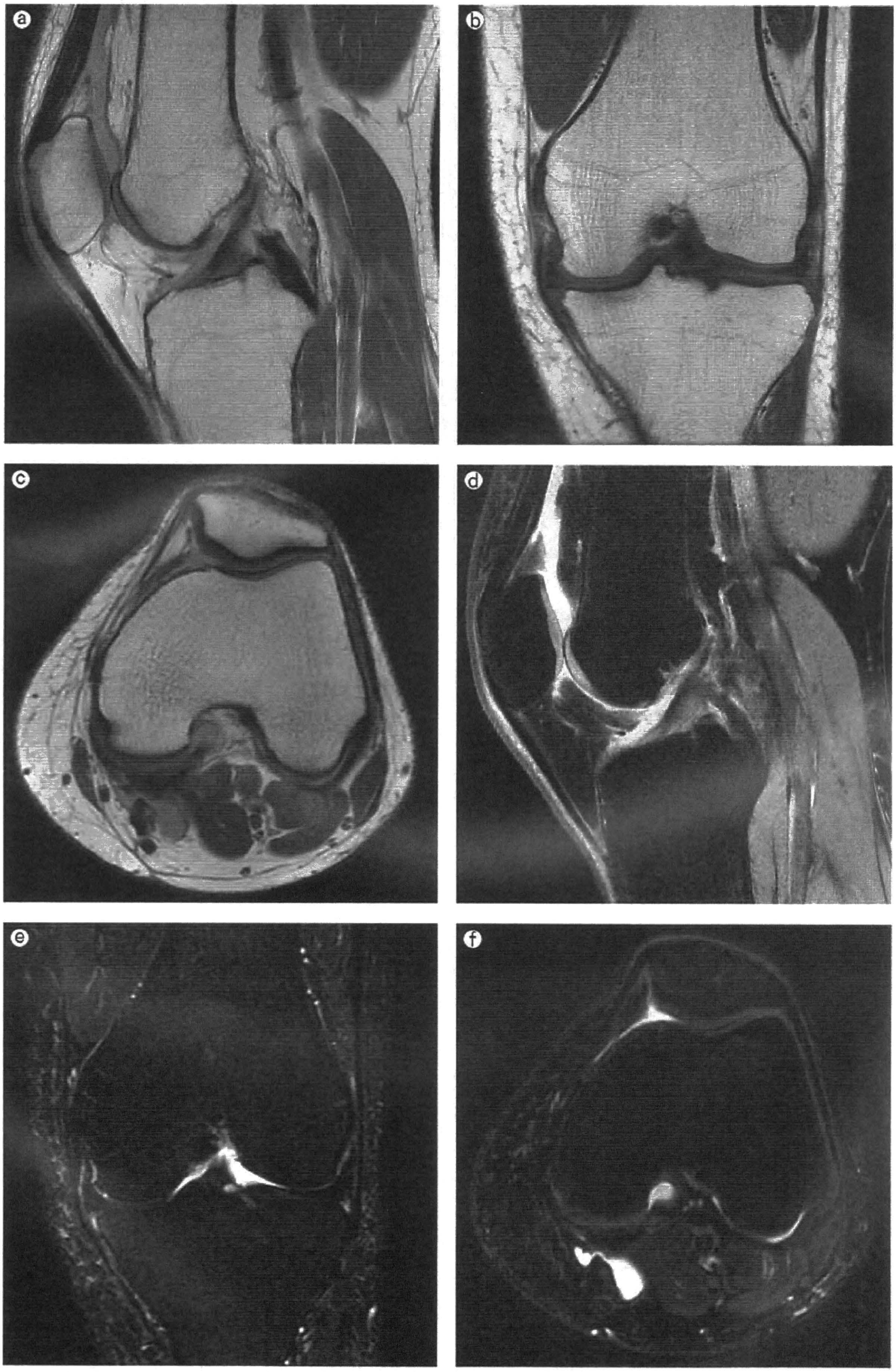
したがって，3D isotropic MRIの実用化には撮像シーケンスの改良も不可欠である。FSE法ではエコートレイン数を増やさざるをえず，画像のぼけ(blurring)につながる。そのため，3D isotropic MRIには，撮像時間を半減させ，またエコートレイン数も調整しやすいパラレルイメージングは非常に有用な技術である。また，少し姑息ではあるが，スライス厚を0.625mmではなく0.7mmに設定し，near-isotropic MRIでもリフォーマット像に画像の劣化がなければ，スライス厚の少しの違いが，撮像時間の短縮にはかなり影響してくる。

Goldら[2)]は，3D-FSE with extended echo-train acquisition(XETA)法を2D-FSE法と比較し，非常に有用な方法だとしている。

その他の3D isotropic MRIの撮像方法として，double-echo steady state(DESS)法があげられる。DESS法は，高速gradient echo(GRE)法で，1つのパルス間隔の間にsteady state precession(FISP)法とreversed FISP(PSIF)法を組み合わせた撮像法である。DESS法では，関節液を高信号，関節軟骨は中間信号に描出される。脂肪抑制法の代わりに水励起(water-excitation)法を加えることで，TRを短く保ったまま，軟骨-軟骨下骨，骨髄間のコントラストも良好となる。

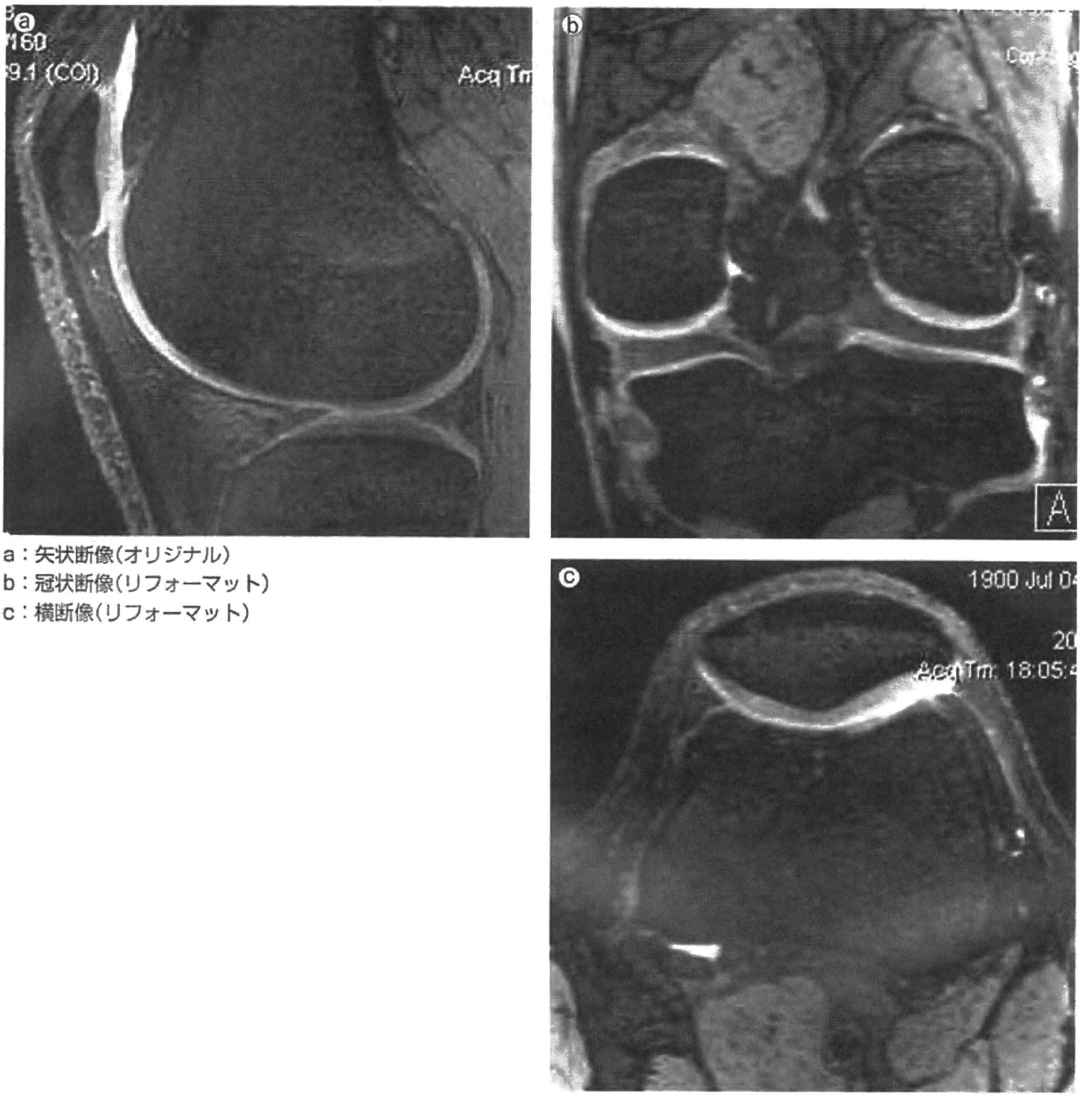
さまざまなコントラストの3D isotropic knee MRIがルーチンの撮像時間内で行えることが理想であるが，現実的には，関節軟骨に限っていえば，PD強調像またはそれに類似の画像(DESSやinter-

図2　3T MRIを用いた膝関節のルーチン撮像



a：PD強調矢状断像，b：T1強調冠状断像，c：PD強調横断像，d：脂肪抑制PD強調矢状断像
e：STIR冠状断像，f：脂肪抑制T2強調横断像

図3　DESS法を用いた膝関節3D isotropic MRI像(0.7×0.7×0.7mm)



a：矢状断像(オリジナル)
b：冠状断像(リフォーマット)
c：横断像(リフォーマット)

mediate TE画像も含む)が脂肪抑制の有無(または通常画像と水励起画像)で，一種類ずつあれば十分である。

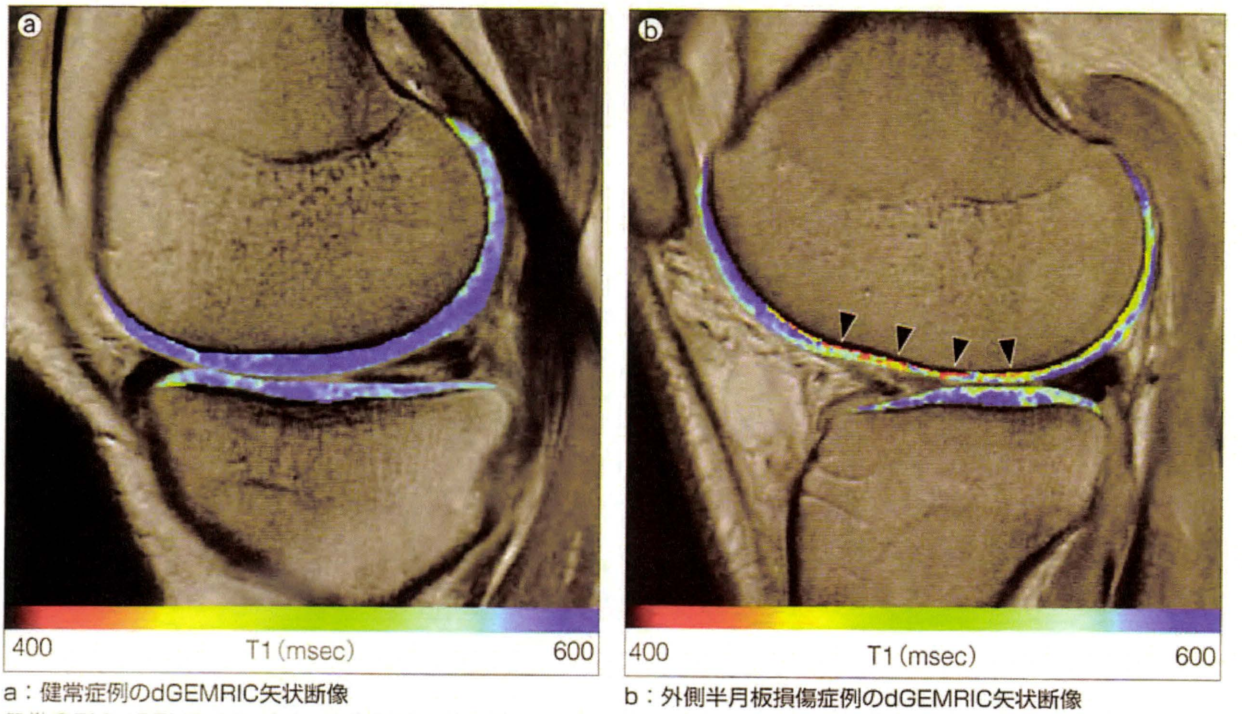
isotropic MRIの最大の利点は，ただ単に細かい高分解能画像が得られるというだけでなく，いったんオリジナルの画像を撮像すれば，それから任意の断面に画像の劣化なくリフォーマットできる点である(**図3**)。通常の矢状断，冠状断，横断像に加え，滑車部の軟骨評価のために，斜冠状断像が必要になったとしても，すべてオリジナルの矢状断像からリフォーマットすることができ，余分な撮像を必要としない。2Dの3つの撮像面(矢状断，冠状断，横断像)がルーチンのプロトコルであるなら，3D isotropic MRIが3つの合計撮像時間より短ければ，スループットに関しても利点があることになる。

また，isotropic MRIでは，細かな病変の確認を複数の撮像断面から行うときも，現在のデジタル画像(ワークステーション)で簡単に位置ずれなくクロスリンクさせることができる。

ただ，最大の問題は，軟骨の3D isotropic MRIで膝関節のほかの病変，たとえば半月板損傷，靱帯損傷の診断も現在使用されている2D-FSEのプロトコルと同程度の感度，特異度であるかという点である。Jungら[3]は，内側半月板，外側半月板，前十字靱帯，および後十字靱帯の損傷に関して

図4　dGEMRICによる膝関節軟骨変性の評価

カラーバーの青色はT1の長い健常部位を，赤色はT1の短い変性部位を示している。



a：健常症例のdGEMRIC矢状断像

健常症例のdGEMRIC像では，関節軟骨は均一で比較的長いT1で示される。

b：外側半月板損傷症例のdGEMRIC矢状断像

20歳代，男性。大腿骨外側顆および脛骨外側顆の軟骨のT1短縮が認められ(▲)，GAG濃度の低下を伴う軟骨変性が示唆される。

0.5×0.5×0.5mmの3D isotropic MRIと2D-FSE MRIを用いて比較したところ，感度，特異度，正確度に関して2つの撮像法間で統計的な有意差はないと報告している。しかし，実際に膝関節MRIのルーチンプロトコルをすべて3D isotropic MRIに置き換えられるかどうかについては，もう少しデータの蓄積が必要であると思われる。

最新の関節軟骨のMRI評価方法

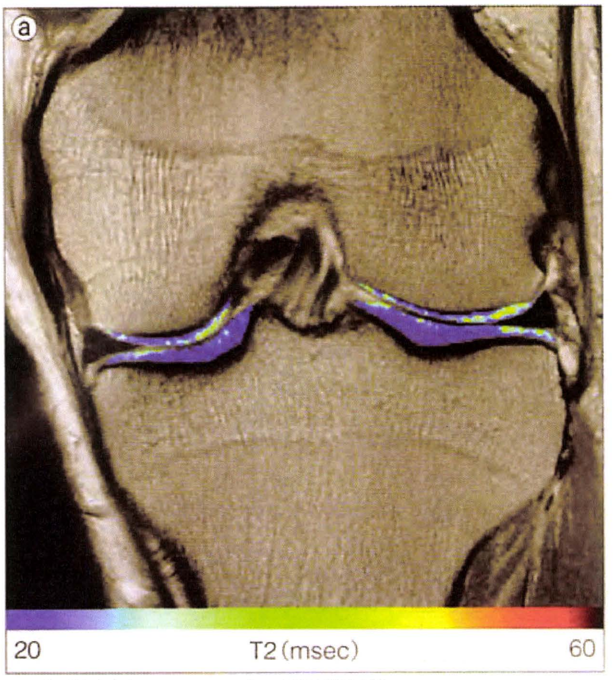
一般的なルーチンMRIは，関節軟骨の形態異常の検出は比較的鋭敏であるものの，軟骨内の信号強度異常の検出に関しては，信号強度自体に定量性がないこともあり，必ずしも鋭敏ではない。このため形態異常や明らかな信号強度異常が出現する以前の，変形性関節症の早期に発生する軟骨変性を詳細に評価することは困難であった。これに対し最近，軟骨の組成や構造の変化などを定量的に評価可能な新しいMRI撮像法が臨床応用されつつあり，軟骨の質的評価に有用な方法として期待されている。ここでは軟骨中の主要構成成分であるグリコサミノグリカン(glycosaminoglycan；GAG)，コラーゲン，水分などの質的評価可能なMRI撮像法について述べる。

dGEMRIC(図4)

dGEMRIC(delayed gadolinium enhanced magnetic resonance imaging of cartilage)[4]は，軟骨中のGAG濃度が評価可能なMRI撮像法であり，早期軟骨変性の検知や軟骨変性度の定量的評価に有用とされる。GAGは陰性荷電を有する極性分子であり，正常軟骨中に豊富に含まれるが軟骨変性に伴って減少する。dGEMRICでは同じく陰性荷電を有するMRI用造影剤(gadopentetate dimeglumine；Gd-$DTPA^{2-}$)を経静脈投与すると，電気的反発力のためGd-$DTPA^{2-}$が軟骨内のGAG濃度と反比例して浸透することを原理としている。すなわち，GAG濃度が低い変性軟骨ほどGd-$DTPA^{2-}$濃度が高くなり，より強いT1短縮が認められる。dGEMRICでは，撮像の約90～120分前にGd-$DTPA^{2-}$を0.2mmol/kgの用量で経静脈投与する。

また，Gd-$DTPA^{2-}$の安定した軟骨内浸透を目的として，投与後に約10分間の荷重歩行を行わせる[5]。Gd-$DTPA^{2-}$は投与後主に関節液を介して軟骨内に

図5 T2マッピングによる膝関節軟骨変性の評価
カラーバーの赤色はT2の長い変性部位を，青色はT2の短い健常部位を示している。



a：健常症例のT2マッピング冠状断像
健常症例のT2マッピング像では，関節軟骨は均一で比較的短いT2で示される。

b：Kellgren-Lawrence分類GradeⅡと分類された内側型膝OA症例のT2マッピング冠状断像
50歳代，女性。大腿骨内側顆および脛骨内側顆の軟骨表層から深層にかけて広範なT2延長が認められ(▲)，コラーゲン配列の不整化や水分含有量の上昇などを伴う軟骨変性が示唆される。

拡散し，撮像時には軟骨全層に安定した拡散が得られる。

dGEMRICではT1計算画像を作成し，GAG濃度の違いをT1の差として定量化するが，一般にはinversion recovery法を用いたsingle slice撮像によるT1測定が行われる。その他3D撮像によるT1測定も行われているが，空間分解能の制限や，repeatabilityの低下などが知られる[6]。

臨床診断の際にはT1計算画像中の軟骨部分を抽出し，T1に基づいてカラーコーディングした画像を作成して視覚的な評価を行っている。またより詳細な定量的評価が必要な場合には，T1計算画像上に関心領域を設定してT1を測定している。

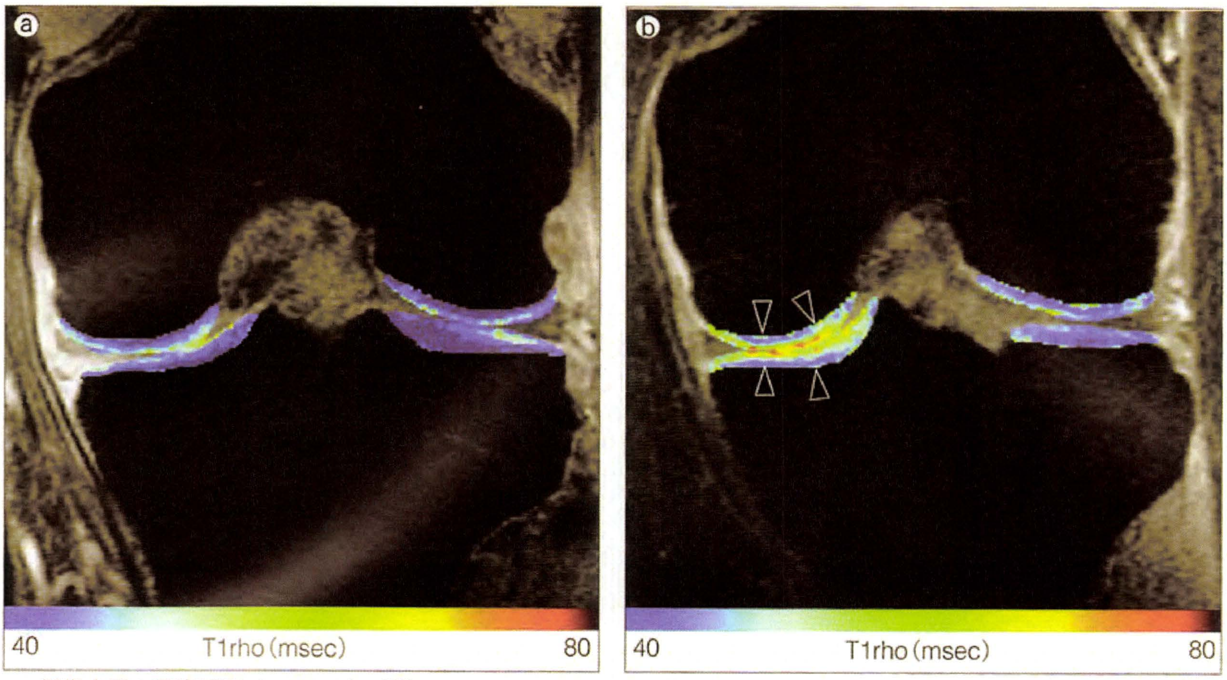
T2マッピング(図5)

T2マッピングは，軟骨中のコラーゲンの配列と水分含有量が評価可能なMRI撮像法であり，dGEMRICと同様に早期軟骨変性の検知や軟骨変性度の定量的評価に有用とされる。正常軟骨は密で規則的に配列するコラーゲンを有し，また水分含有量はほぼ一定に保たれているが，軟骨変性に伴いコラーゲン配列の不整化や水分含有量の増加が進行する。これらの変化はともにT2を延長させるため，変性の進行に従って軟骨のT2は延長する。T2マッピングではT2計算画像を作成し，コラーゲン配列や水分含有量の違いをT2の差として定量化するが，一般にはmulti-spin-echo法を用いたsingle slice撮像によるT2測定が行われる。その他multi-slice撮像によるT2測定も行われるが，SNRの低下やこれに伴うT2の測定誤差を生じる可能性がある[7]。

臨床診断にはT2に基づいてカラーコーディングした画像による視覚的評価を，詳細な定量的評価にはT2計算画像上に関心領域を設定したT2測定を行っている。

図6　T1rhoマッピングによる膝関節軟骨変性の評価

カラーバーの赤色はT1rhoの長い変性部位を，青色はT1rhoの短い健常部位を示している。



a：健常症例の冠状断T1rhoマッピング像

健常症例のT1rhoマッピング像では，関節軟骨は均一で比較的短いT1rhoで示される。

b：Kellgren-Lawrence分類Grade Ⅰと分類された内側型膝OA症例のT1rhoマッピング冠状断像

40歳代，女性。大腿骨内側顆および脛骨内側顆の軟骨表層から深層にかけて広範なT1rho延長が認められ(▲)，GAG濃度の低下や水分含有量の上昇などを伴う軟骨変性が示唆される。

T1rhoマッピング(図6)

T1rho (spin-lattice relaxation in the rotating frame)マッピングは，軟骨中のGAG濃度の評価が可能なMRI撮像法とされる[8]。dGEMRICと比較し造影剤の投与が必要ないため，より非侵襲的な評価が可能である。一方dGEMRICによるT1の変化は，GAG濃度の変化に特異性が高いが，T1rhoマッピングによるT1rhoの変化は，GAGだけでなく水分含有量やコラーゲン配列の変化などにも影響を受けることが知られる[9,10]。変形性関節症(osteoarthritis；OA)の早期に生じる軟骨中のGAG濃度の低下，水分含有量の増加，コラーゲン配列の不整化はともにT1rhoを延長させることから，T1rhoマッピングは早期軟骨変性の有効な指標となるが，いずれのパラメータにも特異性は低いと考えられる。

T1rhoマッピングでは，T1rho計算画像を作成し軟骨変性度を定量化するが，最近は各社から3D T1rhoマッピングの撮像シーケンスが提供されていることもあり，空間分解能などに制限はあるものの，3D撮像によるT1rho測定が行われることが多い[9]。臨床診断にはT1rhoに基づいてカラーコーディングした画像による視覚的評価を，詳細な定量的評価にはT1rho計算画像上に関心領域を設定したT1rho測定を行っている。

UTE MRI

組織はさまざまなT2をもつ構成要素からなるが，T2の短い要素からのmagnetizationは，TEが十分に短くないと評価できない。ultrashort echo time MRI (UTE MRI)は，きわめて短いTEを用いることにより，通常用いられるTEでは検知困難な，組織中のT2の短いコンポーネントの評価が可能なMRI撮像法である[11]。

表1　OAI MRIプロトコル

No.	スキャン
1	localizer (3-plane)
2	sagittal 3D dual-echo steady-state WE
3	coronal IW TSE FS
4	sagittal IW TSE FS
5	coronal T1 3D fast low-angle shot WE
6	sagittal T2 mapping

OAI : osteoarthritis initiative, 3D : three-dimensional, WE : water excited, IW : intermediate-weighted, TSE : turbo spin-echo, FS : fat-suppressed

この方法は骨軟部領域では，半月板，皮質骨，骨膜，腱，靭帯などの病変の評価に用いられるが，関節軟骨ではその最深層にある石灰化層の描出が可能である。石灰化層はOAの初期より変化がみられることが知られており[12]，UTE MRIは初期OAの検知に有用と期待されている。しかしUTE MRIにより捉えられる変化の病的意義などに関してはいまだ不明な点も多く，データの蓄積が必要である。

OAI

Osteoarthritis Initiative (OAI) は，非常にユニークな現在全米の多施設で行われている膝OAの前向き研究(prospective study)，および縦断研究(longitudinal study)である(http://www.oai.ucsf.edu/datarelease/)。OAは，成人において日常生活動作(ADL)の障害の最も一般的な原因となることから，National Institutes of Health (NIH)がスポンサーになって，同疾患の予防と治療の研究を促進するため，現在4年間の観察研究(observation study)を行っている。

この研究のユニークな点は，同疾患の発現や進行を理解するために，画像やバイオマーカー，臨床データなどをすべて公有にして，一般の研究者に公開している点にある。45～79歳の男女約5,000人がこの研究に参加しており，きわめて大規模な研究である。画像に関しては，膝の単純X線写真とMRIを毎年延べ4年間にわたって経過観察することになっており，今年(2010年)3月には，ベースライン，12カ月，24カ月，36カ月のMRIが公開された。MRIは3Tを使用しており，通常膝関節の撮像に使われる2D FSE法のほかに，3D-DESSやT2 mappingのパルスシーケンスが含まれている(表1)。これらの画像データは，OAIに登録し，データユーザー同意書にサインをするだけで利用することができる。実際には，データが十分に収まる容量のハードドライブを研究参加施設の1つであるUniversity of California, San Francisco (UCSF)の担当者に送ると，4～6週以内にデータをコピーして送り返してくれる。また必要なデータ量が少ないときは，UCSFですでに保有しているハードドライブを貸し出してくれ，こちらでコピーし終わったらUCSFに送り返すシステムになっている。

いずれにしても，何百人もの均一なフォローアップデータを，ハードドライブのやり取りだけで簡単に手に入れることができるのは，すばらしいシステムであり，1つの小さな施設では，それほどの数のデータを集めるには，お金も時間もかかるが，公有化により，アイデアさえあればそれらのデータを使ってどんどん研究することができる。OAIのホームページには，データはworld-wideに利用可能であると書いてあるので，興味のある方は，OAIに一度連絡してみてはいかがだろうか。

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Loaded Cartilage T2 Mapping in Patients with Hip Dysplasia[1]

Takashi Nishii, MD
Toshiyuki Shiomi, MD
Hisashi Tanaka, MD
Youichi Yamazaki, MS
Kenya Murase, PhD
Nobuhiko Sugano, MD

Purpose: To evaluate the change in cartilage T2 values with loading in patients with hip dysplasia.

Materials and Methods: Fifteen patients with hip dysplasia and nine asymptomatic healthy volunteers were evaluated between April 2008 and February 2009. All subjects provided written informed consent before participation in this prospective, institutional review board–approved study. Midcoronal T2 mapping of hips was performed under unloaded and loaded conditions (with 50% body weight) at 3.0-T magnetic resonance (MR) imaging. Loading was achieved with a mechanical loading system. T2 values under unloaded conditions and the change in T2 values at the weight-bearing area of the acetabular and femoral cartilage with loading were compared between normal and dysplastic hips. The change in T2 with loading was correlated with the patient's age and body mass index as well as with the center-edge angle determined on conventional radiographs.

Results: The decrease in cartilage T2 at the outer superficial zones of the acetabular cartilage with loading was significantly greater in patients with hip dysplasia than in healthy volunteers: The mean T2 change with loading was −7.6% ± 10.6 (±standard deviation) for dysplastic hips and 1.2% ± 10.9 for normal hips (P = .04). Among patients with hip dysplasia, there was a positive correlation between the center-edge angle on anteroposterior radiographs and T2 changes with loading at the outer deep zones of the acetabular cartilage.

Conclusion: Cartilage T2 mapping with loading during MR imaging enabled the detection of site-specific changes in cartilage T2 in dysplastic hips.

[1] From the Departments of Orthopaedic Medical Engineering (T.N., N.S.), Orthopaedic Surgery (T.N., T.S., N.S.), Radiology (H.T.), and Medical Physics and Engineering, Division of Medical Technology and Science, Faculty of Health Science (Y.Y., K.M.), Osaka University Graduate School of Medicine, 2-2 Yamadaoka, Suita, Osaka 565-0871, Japan. Received October 20, 2009; revision requested December 15; revision received February 17, 2010; accepted March 11; final version accepted March 16. Supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture of Japan. **Address correspondence to** T.N. (e-mail: *nishii@ort.med.osaka-u.ac.jp*).

Hip dysplasia is characterized by insufficient acetabular coverage of the femoral head and is a major cause of hip osteoarthritis (1,2). An abnormal biomechanical environment with elevated contact pressure on the area with limited cartilage is assumed to play a role in the progression of osteoarthritis in patients with hip dysplasia (3–5). Before osteoarthritis progresses, joint-preserving treatments such as weight loss, exercise, and pelvic osteotomy surgery are effective in reducing symptoms and limiting progression (6,7). Thus, it is important to accurately identify patients who are at high risk of osteoarthritis progression and apply joint-preserving treatments for hip dysplasia at a preosteoarthritic or early osteoarthritic stage.

Several morphologic indexes on plain radiographs are widely used to quantify the morphologic characteristics of osteoarthritis, including the center-edge angle, Sharp angle, and acetabular head index (8–10). Although these bone morphologic assessments are related to biomechanics, their prognostic value for estimating osteoarthritic progression is limited (2). Several investigators have used computational-mathematical analysis, including the rigid spring model (11,12) and finite element analysis (13–16), to estimate the biomechanical conditions of hip articular cartilage. To our knowledge, however, no biomechanical analysis can enable direct evaluation of load distribution on the cartilage of the hip joint in vivo.

The load responsiveness of articular cartilage has been experimentally studied by using magnetic resonance (MR) imaging and excised cartilage-bone plugs (17,18), and site-specific signal intensity changes along the cartilage depth were observed in response to the magnitude of applied compression force. This change in signal intensity is assumed to be caused by water extrusion or a change in the collagenous structure within the cartilage (17,19). Currently, several quantitative MR imaging techniques for cartilage assessment have been developed, including delayed gadolinium-enhanced MR imaging of cartilage and T2, T1ρ and sodium MR imaging, and diffusion-weighted MR imaging (20–22). The findings of these examinations correlate with changes in the cartilage's extracellular matrix, including changes in proteoglycans, collagen, and water (19–24).

We hypothesized that comparison between quantitative MR parameters under unloaded and loaded conditions in vivo could be useful in detecting a critical cartilage area with elevated contact pressure by enabling quantitative evaluation of the change of collagenous architecture or of the water influx or efflux of the cartilage (19,23,24). Hence, we developed a loading apparatus that applies an axial load to the hip joint during MR imaging to simulate physiologic load-bearing conditions upon standing. Among the quantitative MR imaging techniques for cartilage assessment, we chose T2 mapping because (*a*) T2 has shown a close correlation with collagenous architecture and water content (23,24) and (*b*) there is a zone-specific change in T2 along the cartilage depth in response to external loading (18). The purpose of this study was to examine the change in T2 maps with loading during MR imaging to detect site-specific changes in cartilage T2 in patients with hip dysplasia.

Materials and Methods

Institutional review board approval was obtained for this study, and all subjects provided written informed consent after the nature of the procedure had been fully explained.

Study Population

Nine healthy volunteers (nine hips) and 15 patients with hip dysplasia (15 hips) were included in this study between April 2008 and February 2009. Because most patients with hip dysplasia are women (25), men were excluded from this study to prevent the potentially confounding influence of sex on T2 mapping of articular cartilage (26). Volunteers were excluded if they were currently experiencing or had previously experienced hip pain, stiffness, limitation in the range of hip motion, or gait disability. Patients with hip dysplasia were included if they had not previously undergone hip surgery and had a center-edge angle of 24° or less on anteroposterior radiographs (27). Patients were also included if they had a class I subluxation (<50%) according to the classification used by Crowe et al (28) and preosteoarthritis or early radiologic osteoarthritis according to the Kellgren-Lawrence classification (29) of grade 0 (no osteoarthritic finding), grade 1 (possible narrowing of joint space and/or osteophytes), or grade 2 (definite narrowing of joint space, definite osteophytes, and slight sclerosis). In a previous study (30), the Kellgren-Lawrence classification of hip osteoarthritis was determined to provide sufficient interobserver reproducibility and

Advance in Knowledge

- Loaded cartilage T2 mapping showed that patients with hip dysplasia had a significantly larger decrease of cartilage T2 at the outer superficial zones of the acetabular cartilage compared with healthy volunteers.

Implication for Patient Care

- Loaded cartilage T2 mapping with use of in situ MR imaging enables the detection of site-specific changes in cartilage T2 with loading in dysplastic hips.

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Abbreviations:
ROI = region of interest
WOMAC = Western Ontario and McMaster Universities

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