Original Article

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Analysis of Mechanical Loading after Anatomic Anterior Cruciate Ligament Reconstruction Using Combined Single-Photon Emission Computerized Tomography and Conventional Computerized Tomography

Byung Kag Kim, MD[1], Tae Won Kim, MD[2], Chul Ho Hwang, MD[2], Hong Ki Park, MD[2], Kyung Hoon Hwang, MD[3], Jae Ang Sim, MD[2], Yong Seuk Lee, MD[4], and Beom Koo Lee, MD[5]

[1]Department of Orthopedic Surgery, Joint Center, Sungmin Hospital, Incheon; [2]Department of Orthopedic Surgery, Gil Medical Center, Incheon; [3]Department of Nuclear Medicine, Gil Medical Center, Incheon; [4]Department of Orthopedic Surgery, Seoul National University Bundang Hospital, Seongnam; [5]Department of Orthopedic Surgery, The Armed Forces Capital Hospital, Incheon, Korea

Purpose: This study was to evaluate changes of the mechanical loading pattern after anatomic anterior cruciate ligament (ACL) reconstruction by analyzing uptake patterns using combined single-photon emission computerized tomography and conventional computerized tomography (SPECT/CT).

Materials and Methods: On SPECT/CT, high signal intensity of the articular surface which shows biological activity and mean increase of mechanical loading was compared with that of the tibiofemoral shaft as a comparative signal. The proportion of positive signals was evaluated in all compartments of the operated knee. Analysis was performed according to combined injury.

Results: A relatively high proportion of positive signals was detected in the posterior zone of the lateral tibial plateau (23.5%) and trochlear groove (23.5%) although increased signal intensity was detected in all compartments. There was no statistical difference depending on the presence of combined injury and between single-bundle and double-bundle ACL reconstruction.

Conclusions: Following anatomic ACL reconstruction, higher signal intensity was detected, particularly in the posterior part of the lateral tibial plateau and trochlear groove. Close observation for further signal changes or osteoarthritic changes would be required even if there was no combined injury and anatomic reconstruction was performed.

Keywords: **Knee, Anterior cruciate ligament, Reconstruction, Computerized tomography, SPECT**

Introduction

An anterior cruciate ligament (ACL) injury could lead to arthritic changes due to a cartilage injury, meniscal tear, and the secondary laxity of capsule and ligaments caused by repetitive subluxation of the knee joint. Therefore, it could be assumed that restoration of knee joint stability may decrease the risk of early osteoarthritis. According to a meta-analysis by Ajuied et al.[1], ACL injury predisposes the knees to osteoarthritis, while ACL reconstruction surgery contributes to reduction in the 10-year risk of developing osteoarthritis.

ACL reconstruction using bone-patellar tendon-bone autograft resulted in high patient satisfaction levels and good clinical results after 10 years; however, 17.8% of the patients developed knee osteoarthritis[2], and the onset of osteoarthritis was observed in over 40% of patients after a mean follow-up period of 10 years following ACL reconstruction[3].

Several studies have shown that development of osteoarthritis after ACL reconstruction is mainly influenced by concomitant injuries to the meniscus, other ligaments, cartilage, and subchon-

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Correspondence to: Beom Koo Lee, MD
Department of Orthopedic Surgery, The Armed Forces Capital Hospital, Saemaeul-ro 177beon-gil, Bundang-gu, Seongnam 13574, Korea
Tel: +82-31-725-6162, Fax: +82-31-725-6129
E-mail: knee5360@naver.com

dral bone. It could also be caused by an abnormal loading pattern after non-anatomic ACL reconstruction[3-6].

As a result, early detection of the osteoarthritic change could be indirectly performed by observing changes in the mechanical loading pattern using combined single-photon emission computerized tomography and conventional computerized tomography (SPECT/CT)[7,8]. SPECT/CT is a hybrid imaging modality combining three-dimensional (3D) bone scintigraphy (SPECT) and conventional CT into one imaging procedure. It has been used for several years in cardiology and neurology, but only recently in orthopedics[7-10]. SPECT/CT can correlate the biological activity observed on SPECT with the exact anatomic region observed on CT; therefore, the clinical uses of SPECT/CT are increasing[7-14]. Use of the signal pattern on SPECT/CT in the early detection of osteoarthritis has been suggested[7].

However, whether a combined injury could cause a further increase in the signal intensity and anatomic ACL reconstruction could restore normal mechanical loading pattern is questionable. Therefore, the purpose of this study was to evaluate the mechanical and biological changes in the knee joint after ACL reconstruction by analyzing the SPECT/CT uptake patterns.

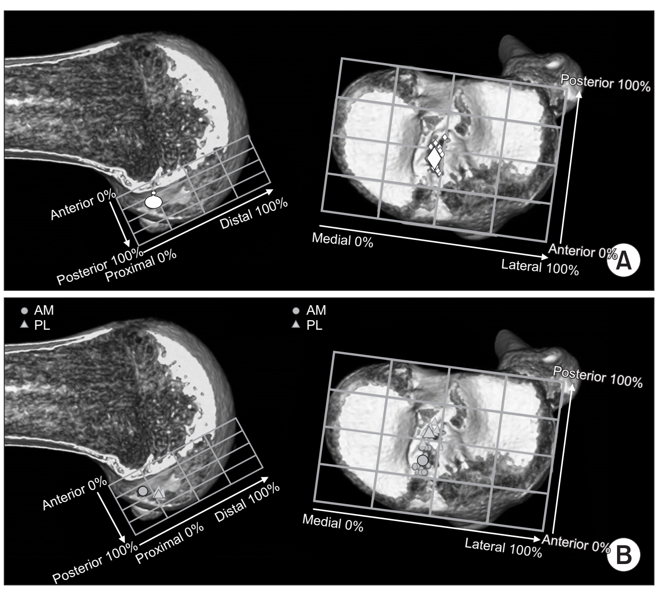

Fig. 1. Tunnel positions in anatomic anterior cruciate ligament reconstruction. Femoral and tibial tunnel positions of each case were identified on the computed tomography scan. The tunnel positions of each case corresponded approximately to the anatomic footprint. (A) Single-bundle reconstruction. (B) Double-bundle reconstruction. AM: anteromedial, PL: posterolateral.

Materials and Methods

1. Materials

From 2006 to 2014, anatomic ACL reconstruction was performed on 314 patients in our hospital and anatomic tunnel location was confirmed with postoperative CT (Fig. 1). SPECT/CT was performed in some of these patients postoperatively. Among those, 34 patients (28 males and 6 females) with closed epiphysis who were followed up for a minimum postoperative period of 1 year were included. We wanted to enroll all patients who had undergone ACL reconstruction from 2006 to 2014; however, only 34 patients could be enrolled because we began performing SPECT/CT in 2013. In all cases, SPECT/CT was performed after a postoperative period of 1 year (average, 18 months; range, 12 to 84 months). At the time of surgery, the mean age of the patients was 29.4 years (range, 17.4 to 45.6 years). Informed consent was obtained from all patients before performing SPECT/CT, and this study was approved by the Institutional Review Board of our hospital before commencing the study.

2. Methods of Uptake Analysis on SPECT/CT

The signals of the articular surface in the medial compartment, lateral compartment, and patellofemoral compartment were evaluated (Fig. 2). The medial compartment was divided into 4 zones (medial femoral condyle: 2 zones, anterior zone and posterior

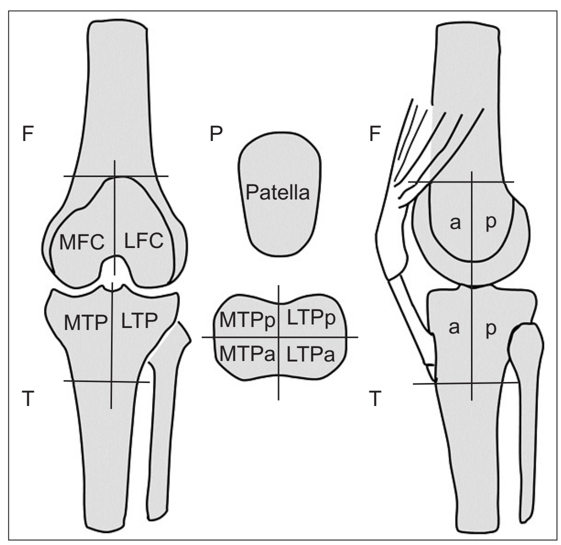

Fig. 2. The mapping scheme used for localization of uptake areas of single-photon emission computerized tomography and conventional computerized tomography. MFC: medial femoral condyle, LFC: lateral femoral condyle, MTP: medial tibial plateau, LTP: lateral tibial plateau, MTPp: posterior zone of the MTP, MTPa: anterior zone of the MTP, LTPp: posterior zone of the LTP, LTPa: anterior zone of the LTP, a: anterior zone, p: posterior zone.

zone; medial tibial plateau: 2 zones, anterior zone and posterior zone) in the sagittal plane and the lateral compartment was divided into 4 zones (lateral femoral condyle: 2 zones, anterior zone and posterior zone; lateral tibial plateau: 2 zones, anterior zone and posterior zone) in the sagittal plane. The patellofemoral compartment was divided into 2 zones (patella facet and trochlea) in the axial plane. The signal intensity was compared with the tibiofemoral shaft as a comparison group, which showed no signal in all patients. In this comparison, the brighter signal was marked as a positive signal and the same signal intensity as the comparison group was marked as a negative signal (Fig. 3). The proportion of positive signals in each compartment of all 34 patients was statistically evaluated. Signal data were compared between one group with combined meniscal injury (only medial meniscus, 5 out of 34 cases; only lateral meniscus, 6 out of 34 cases) and the other group without combined injury (15 out of 34 cases). In addition, all signal data were also compared between the anatomic single-bundle (SB) ACL reconstruction group (16 out of 34 cases) and the anatomic double-bundle (DB) ACL reconstruction group (18 out of 34 cases). The evaluation of signal intensity was performed independently by one orthopedic surgeon and one radiologist who had no association with the surgery performed on the patients and the evaluation results were identical between these two observers (Cohen's kappa coefficient, 1).

3. Statistical Analysis

Statistical analysis of the signal data of each group was performed using IBM SPSS ver. 22.0 (IBM Corp., Armonk, NY, USA) and each group was compared using chi-square test or Fisher exact test. For statistical analysis of interobserver agreement, Cohen's kappa coefficient was used.

Results

The results of evaluation by these two observers were in complete agreement (Cohen's kappa coefficient, 1). There was no statistical difference in the postoperative period of SPECT/CT follow-up and mean age between the anatomic SB ACL reconstruction group and the anatomic DB ACL reconstruction group. The classification of patients according to combined injuries and surgical techniques is shown in Table 1.

Different signal patterns on the articular surface were detected according to specific compartments. Among these, a relatively high proportion of positive signals was detected in the posterior zone of the lateral tibial plateau (23.5%) and trochlea (23.5%) (Fig. 3C). However, no positive signals were detected in both posterior zones of the medial femoral condyle (0%) and the anterior zone of the lateral tibial plateau (0%) in all patients (Fig. 4).

The signal pattern in the posterior zone of the lateral tibial

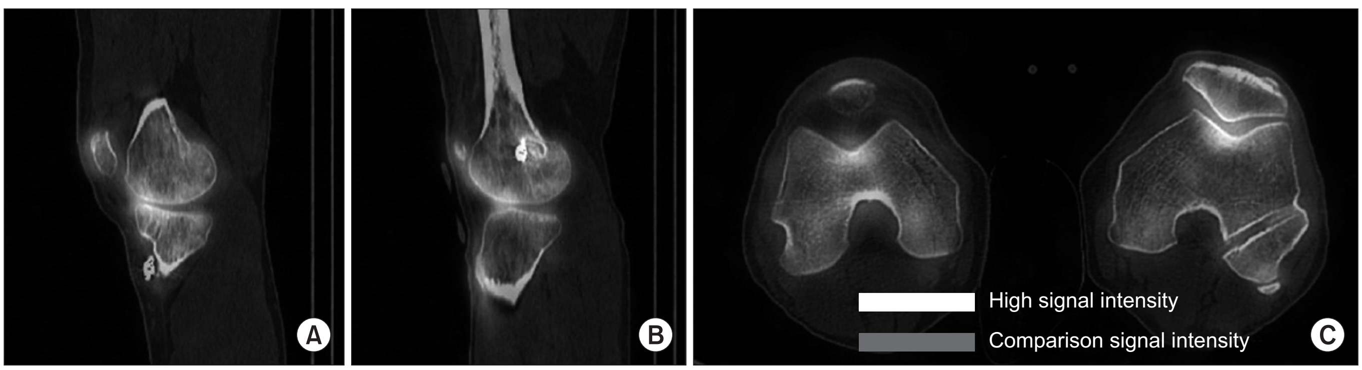

Fig. 3. High signal intensity on the single-photon emission computerized tomography and conventional computerized tomography image appears in white, while the comparison signal intensity in the tibiofemoral shaft appears in gray. (A, B) The medial and lateral compartments were divided into 4 zones in the sagittal plane. (C) The trochlea showed high signal intensity indicating high biological activity.

Table 1. Classification of Patients according to Combined Injury and Surgical Technique

ACLR	Combined injury (–)	Combined injury (+)					
		MM only	LM only	LCL only	MM, LM	MM, LCL	MCL only
Single-bundle (N=16)	6	1	3	2	1	1	0
Double-bundle (N=18)	9	4	3	0	2	2	0

ACLR: anterior cruciate ligament reconstruction, MM: medial meniscus, LM: lateral meniscus, LCL: lateral collateral ligament, MCL: medial collateral ligament.

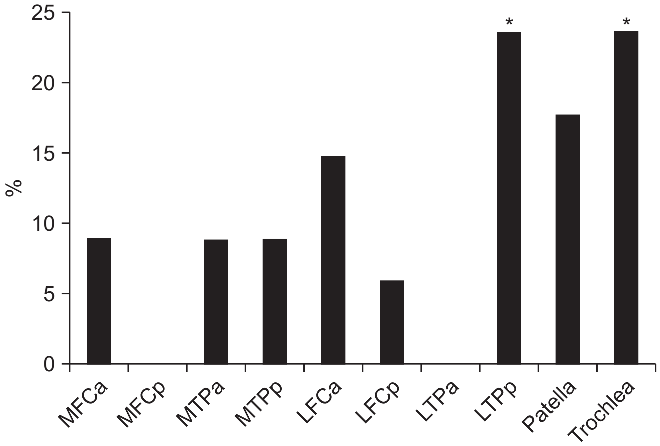

Fig. 4. Positive signal rates differed according to compartments in all 34 cases. Relatively high proportions (*) of positive signals were detected in the posterior zone of the lateral tibial plateau (LTPp, 23.5%) and trochlea (23.5%). MFCa: anterior zone of the medial femoral condyle, MFCp: posterior zone of the medial femoral condyle, MTPa: anterior zone of the medial tibia plateau, MTPp: posterior zone of the medial tibia plateau, LFCa: anterior zone of the lateral femoral condyle, LFCp: posterior zone of the lateral femoral condyle, LTPa: anterior zone of the lateral tibial plateau.

Table 2. Difference in Signal Patterns between No Combined Injury Group and Medial Meniscus (MM) Combined Injury Group

Zone	Combined injury (–) (N=15)	MM combined injury (N=5)	p-value
Medial tibial plateau posterior	1 (6.7)	2 (40)	0.14
Lateral femoral condyle anterior	1 (6.7)	1 (20)	0.447
Lateral femoral condyle posterior	0 (0)	1 (20)	0.25
Lateral tibial plateau posterior	1 (6.7)	2 (40)	0.14
Patella	4 (26.7)	1 (20)	0.634
Trochlea	3 (20)	1 (20)	0.751

Values are presented as number (%).

Table 3. Difference in Signal Patterns between No Combined Injury Group and Lateral Meniscus (LM) Combined Injury Group

Zone	Combined injury (–) (N=15)	LM combined injury (N=5)	p-value
Medial femoral condyle anterior	0 (0)	1 (16.7)	0.286
Medial tibial plateau anterior	0 (0)	1 (16.7)	0.286
Medial tibial plateau posterior	1 (6.7)	0 (0)	0.714
Lateral femoral condyle anterior	1 (6.7)	1 (16.7)	0.5
Lateral tibial plateau posterior	1 (6.7)	3 (50)	0.053
Patella	4 (26.7)	0 (0)	0.228
Trochlea	3 (20)	1 (16.7)	0.684

Values are presented as number (%).

Table 4. Difference in Signal Patterns between Single-Bundle (SB) and Double-Bundle (DB) Anterior Cruciate Ligament Reconstruction (ACLR)

Zone	SB ACLR (N=16)	DB ACLR (N=18)	p-value
MFC anterior	3 (18.8)	0 (0)	0.094
MFC posterior	0 (0)	0 (0)	-
MTP anterior	2 (12.5)	1 (5.6)	0.455
MTP posterior	0 (0)	3 (16.7)	0.136
LFC anterior	3 (18.8)	2 (11.1)	0.441
LFC posterior	1 (6.3)	1 (5.6)	0.727
LTP anterior	0 (0)	0 (0)	-
LTP posterior	2 (12.5)	6 (33.3)	0.153
Patella	2 (12.5)	4 (22.2)	0.389
Trochlea	6 (37.5)	2 (11.1)	0.08

Values are presented as number (%).
MFC: medial femoral condyle, MTP: medial tibial plateau, LFC: lateral femoral condyle, LTP: lateral tibial plateau.

plateau showed no statistical correlation with detection of bone bruise on the preoperative magnetic resonance imaging (MRI) (p=0.613). Twenty-two patients had bone bruises, and 10 patients had no bone bruises in the posterior zone of the lateral tibial plateau on the preoperative MRI, and there was no preoperative MRI in 2 patients. However, these bone bruises had disappeared completely on MRI performed after a postoperative period of minimum 1 year in all 22 patients. Therefore, we confirmed that there was no relationship between the SPECT/CT signal and bone bruise.

There was no statistical difference in signal patterns of all compartments between the group with combined medial or lateral meniscus injury and the group without combined injury (Tables 2 and 3).

In addition, there was no statistical difference in signal patterns of all compartments between the anatomic SB ACL reconstruction group and the anatomic DB ACL reconstruction group (Table 4).

Discussion

The main results of this study were that (1) a relatively high proportion of the positive signals was detected in the posterior zone of the lateral tibial plateau (23.5%) and trochlear groove (23.5%), although increased signal intensity was detected in all compartments, (2) there was no statistical difference in terms of the presence of combined injury and (3) there was no statistical difference between SB and DB ACL reconstruction.

Anatomic ACL reconstruction is the treatment of choice after complete ACL rupture. However, it cannot completely protect the knees from posttraumatic arthritic changes and can only decrease the progression of posttraumatic arthritic changes to a certain extent. According to a meta-analysis by Ajuied et al.[1)], ACL injury predisposes the knees to osteoarthritis, while ACL reconstruction surgery can be helpful in reducing the risk of developing degenerative changes in a postoperative period of 10 years. Although anterior laxity was found restored during KT-1000 arthrometer testing after ACL reconstruction, normal tibiofemoral kinematics was not restored especially under weight bearing condition in spite of reduction of sagittal laxity within normal limits[15,16)]. The lack of a functionally normal ACL would change the static and dynamic loading of the knee, leading to secondary injuries of the cartilage and other joint structures. The knee with a reconstructed ACL is not the same as the normal knee and over the course of years after the trauma, the injured knee, whether reconstructed or not, would be subject to an abnormal loading pattern in everyday activities, thus significantly increasing the risk of osteoarthritis[6)].

There are two methods of anatomic ACL reconstruction: anatomic SB ACL reconstruction and anatomic DB ACL reconstruction. Many studies have reported on differences between the two methods. DB ACL reconstruction may produce better biomechanical outcome, especially under rotator loads[17)]. During a minimum 2-year follow-up, DB ACL reconstruction showed better VAS, anterior knee laxity, and final objective IKDC scores than SB ACL reconstruction[18)]. Morimoto et al.[19)] suggested that changes in the contact area and pressure after SB ACL reconstruction might be a cause of osteoarthritis in a long-term follow-up; on the other hand, DB ACL reconstruction might reduce the incidence of osteoarthritis by closely restoring the contact area and pressure. However, the subjective and objective clinical scores showed no statistical difference between the two methods despite the significant improvement in anterior and rotational stability after DB ACL reconstruction[20)]. DB ACL reconstruction is technically more complex and time-consuming than SB ACL reconstruction, thus it is questionable whether DB ACL reconstruction is required to restore a normal pivot-shift sign[21)]. There were no significant differences in terms of complications and the clinical outcomes between the two procedures, although postoperative anterior and rotational stability after anatomic DB ACL reconstruction was significantly better than that after SB ACL reconstruction[22)].

In this study, we confirmed that there was no statistical difference in signal patterns between the anatomic SB ACL reconstruction group and the anatomic DB ACL reconstruction group on SPECT/CT, meaning that there were no differences between the two reconstruction methods with regard to prevention of osteoarthritis. The clinical uses of SPECT/CT have recently increased because it can correlate the biological activity observed on SPECT with the exact anatomic region observed on CT[7-14)].

However, although SPECT/CT has recently proven useful as a diagnostic tool in orthopedics, the clinical adoption has been limited due to shortcomings of available analytical tools. SPECT analyses are mainly qualitative due to variation in the overall metabolic uptake among patients and most analyses are performed in 2D, despite the availability of rich 3D data. Consequently, quantitative comparison of the position, size, and intensity of SPECT uptake regions among patients is difficult, and therefore drawing meaningful clinical conclusions is difficult[9)]. In this study, using statistical analysis, we were able to confirm that the signal of specific compartments on SPECT/CT after ACL reconstruction increased significantly in the postoperative period of minimum 1 year. Although we did not compare with a control group with uninjured ACL, based on the mechanical loading pattern of the knee joint after ACL reconstruction, it appeared that degenerative osteoarthritis would progress even after anatomic ACL reconstruction because of the increased mechanical loading of specific compartments.

The limitations of this preliminary study were as follows: first, uptake signal on SPECT/CT was not analyzed quantitatively but only qualitatively. Second, because we had no data on patients in a control group who had undergone a conservative treatment we could not confirm that the increased signal pattern was a result of ACL injury or iatrogenic change by surgery. Third, preoperative SPECT/CT image scanning was not performed, thus we could not perform a comparison between the preoperative state and postoperative state. In addition, relationship of the results obtained by SPECT/CT with those obtained using other radiological methods and actual demonstration of degenerative osteoarthritis should be confirmed by long-term follow-up. Finally, in this study, we did not consider individual patient-associated variables such as the extent of initial injury, physical activity levels, muscle strength, body mass index, rehabilitation for a postoperative period of 1 year, and return to sports activity. However, the most important limitation was that the number of patients was insufficient, thus we could only conduct a preliminary study. Based on this preliminary study, inclusion of an adequate number of cases and performance of a power analysis for calculation of sample size would be required in future studies.

Conclusions

Following anatomic ACL reconstruction, higher signal intensity was detected, particularly in the posterior part of the lateral tibial plateau and trochlear groove, which means that biological activity increases and osteoarthritis is more likely to occur in these regions. There was no difference according to the presence of combined injury and between SB and DB ACL reconstruction. Therefore, close observation would be required to determine whether further signal changes or osteoarthritic changes will occur even if there was no combined injury and anatomic reconstruction was performed.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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