Ideal Combination of Anatomic Tibial and Femoral Tunnel Positions for Single-Bundle ACL Reconstruction

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Background: Anatomic anterior cruciate ligament reconstruction (ACLR) is preferred over nonanatomic ACLR. However, there is no consensus on which point the tunnels should be positioned among the broad anatomic footprints.

Purpose/Hypothesis: To identify the ideal combination of tibial and femoral tunnel positions according to the femoral and tibial footprints of the anteromedial (AM) and posterolateral (PL) anterior cruciate ligament bundles. It was hypothesized that patients with anteromedially positioned tunnels would have better clinical scores, knee joint stability, and graft signal intensity on follow-up magnetic resonance imaging (MRI) than those with posterolaterally positioned tunnels.

Study Design: Cohort study; Level of evidence, 3.

Methods: A total of 119 patients who underwent isolated single-bundle ACLR with a hamstring autograft from July 2013 to September 2018 were retrospectively investigated. Included were patients with clinical scores and knee joint stability test results at 2-year follow-up and postoperative 3-dimensional computed tomography and 1-year postoperative MRI findings. The cohort was divided into 4 groups, named according to the bundle positions in the tibial and femoral tunnels: AM-AM (n = 33), AM-PL (n = 26), PL-AM (n = 29), and PL-PL (n = 31).

Results: There were no statistically significant differences among the 4 groups in preoperative demographic data or postoperative clinical scores (Lysholm, Tegner, and International Knee Documentation Committee subjective scores); knee joint stability (anterior drawer, Lachman, and pivot-shift tests and Telos stress radiographic measurement of the side-to-side difference in anterior tibial translation); graft signal intensity on follow-up MRI; or graft failure.

Conclusion: No significant differences in clinical scores, knee joint stability, or graft signal intensity on follow-up MRI were identified between the patients with anteromedially and posterolaterally positioned tunnels.

Keywords: knee ligaments; ACL; magnetic resonance imaging; anatomy

The anterior cruciate ligament (ACL) plays an important role in current sports medicine, as patients with ACL injuries are young, and the rate of ACL reconstruction (ACLR) increases markedly over time in all age groups.[6,18,30] The annual reported incidence of ACL tears is 68.6 per 100,000 person-years and peaks between 19 and 25 years in male patients and between 14 and 18 years in female patients.[30] Many studies[6,7,9,24,31,37] have identified factors that affect the outcomes of ACLR. Some studies[8,16,26] have suggested that anatomic ACLR is preferred over nonanatomic ACLR (isometric). Current studies[23,27,29,32,37] have shown that proper positioning of the anteromedial (AM) and posterolateral (PL) ACL bundles of the tibial and femoral tunnels is important for successful ACLR. There has been 1 biomechanical study[12] and no comparative clinical studies considering anatomic tibial and femoral tunnel positions simultaneously. This is necessary because a combination of the 2 positions will help decide the ACL graft length, shape, tension, and action.

The purpose of this study was to find a clinically ideal combination of anatomic ACL tunnel positions. We hypothesized that patients with anteromedially positioned tunnels would have better clinical scores, knee joint stability, and graft signal intensity on follow-up magnetic resonance imaging (MRI) than those with posterolaterally positioned tunnels.

METHODS

Patient Selection and Study Design

After obtaining approval from our institutional review board, we retrospectively reviewed the medical records and

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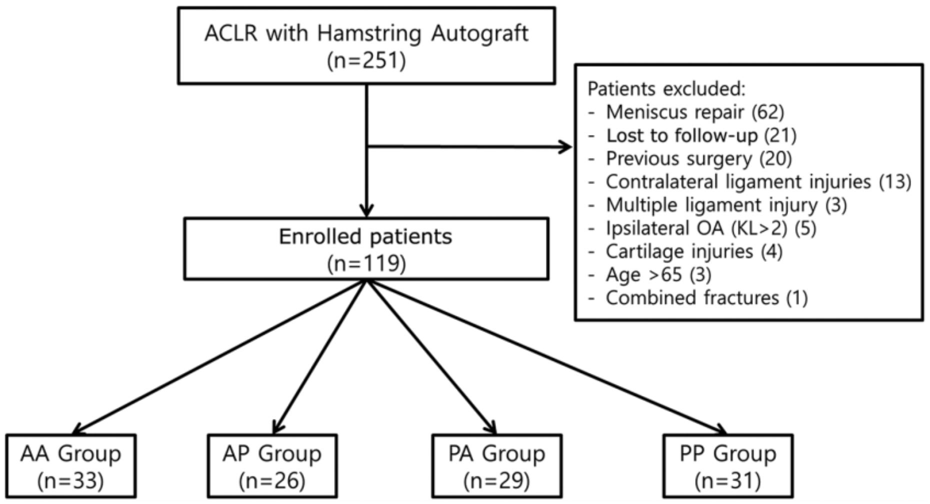

Figure 1. Flowchart of patient enrollment. Patients were divided into 4 groups, named according to the anteromedial (AM) or posterolateral (PL) bundle positions in the tibial and femoral tunnels. AA group: Tibial and femoral tunnels are close to the AM bundle. AP group: Tibial tunnel is near the AM bundle, and the femoral tunnel is near the PL bundle. PA group: Tibial tunnel is near the PL bundle, and the femoral tunnel is near the AM bundle. PP group: Tibial and femoral tunnels are close to the PL bundle. ACLR, anterior cruciate ligament reconstruction; KL, Kellgren-Lawrence; OA, osteoarthritis.

radiologic data of 251 patients treated with ACLR between June 2013 and September 2018 per the following inclusion criteria: autologous hamstring tendon graft, AM transportal technique, femoral suspensory fixation, and tibial biodegradable interference screw fixation. ACL rupture was diagnosed via clinical examination, stress radiography, and MRI. The exclusion criteria were as follows: concomitant meniscal repair surgery, lost to follow-up, previous ipsilateral surgery, contralateral ligamentous injury, multiligamentous injury, ipsilateral osteoarthritis (Kellgren-Lawrence grade >2), cartilage injuries requiring surgical treatment (eg, microfracture and autologous chondrocyte formation on the ipsilateral knee), age >65 years, and combined fracture.

Patient Classification

After exclusions, 119 patients were enrolled in the study: 103 male and 16 female patients (mean ± SD age, 28.7 ± 11.39 years; range, 14-62 years). The mean follow-up period was 36.4 ± 14.7 months. The patients were divided into 4 groups according to the position of the tibial and femoral tunnels (Figure 1):

AA: tibial and femoral tunnels near the AM bundle (n = 33)
AP: tibial tunnel near the AM bundle, femoral tunnel near the PL bundle (n = 26)
PA: tibial tunnel near the PL bundle, tibial tunnel near the AM bundle (n = 29)
PP: tibial and femoral tunnels near the PL bundle and the center (n = 31)

AM and PL Tunnel Positions

The positions of the tibial and femoral tunnels were identified through postoperative 3-dimensional computed tomography (3D-CT; Philips). The 3D-CT was performed in all patients before they were discharged from the hospital, and the reconstructed images for the femoral and tibial tunnels were used to classify the patients into the study groups. For the femoral tunnel position, a true lateral view was obtained, displaying the medial wall of the lateral condyle with neutral rotation, which was reported to show high correlation and reproducibility by Kim et al.[14] The femoral tunnel position was located using the quadrant method of Bernard et al[2] on the 3D-CT reconstruction image. Several studies[5,13,15,34,38-40] have reported the anatomic femoral

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Ethical approval for this study was obtained from Kyung Hee University Hospital (2020-09-077).

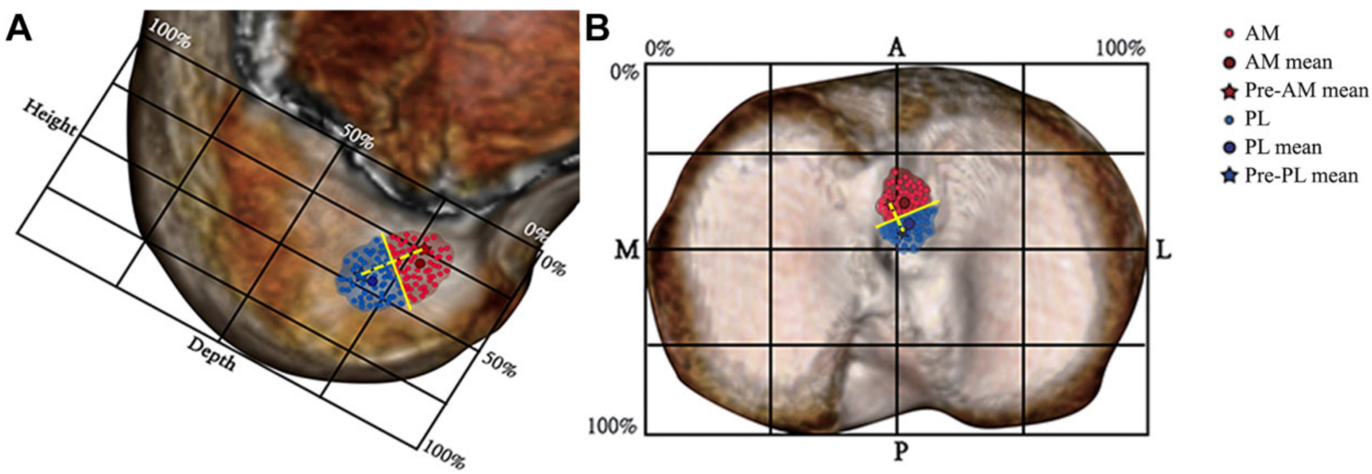

Figure 2. Reconstructed 3-dimensional computed tomography images of the femoral and tibial tunnels. The red star indicates the pre-AM mean, defined as the anatomic position of the AM bundle of the femoral tunnel. The blue star indicates the pre-PL mean. The dashed yellow line connects the 2 stars, and the yellow line bisecting it divides the ACL footprint into the AM and PL groups. Small red and blue dots indicate the individual tunnels of the enrolled patients as classified by the bisecting line. The large red and blue circles indicate the mean location of the AM and PL groups, respectively. (A) Lateral view on the medial wall of the lateral femoral condyle demonstrating the 4-quadrant method. (B) The tibial locations of the ACL tunnel centers were measured as percentages of the anteroposterior and mediolateral distances on the tibial plateau from the anterior and medial borders, respectively. A, anterior; ACL, anterior cruciate ligament; AM, anteromedial; L, lateral; M, medial; P, posterior; PL, posterolateral.

footprints of the ACL bundles using the quadrant method, with mean locations for the AM bundle (23.6% in depth, 21.2% in height) and PL bundle (32.6% in depth, 48.2% in height). We defined the mean AM and PL locations based on these previous studies as pre-AM mean and pre-PL mean (expressed as red and blue stars in Figure 2A). A line was drawn connecting the 2 points, and an additional bisecting line was drawn to divide an ACL footprint. The femoral tunnel positions were also obtained and marked with the quadrant method, and the tunnels close to the pre-AM mean were included in the AM group while the tunnels close to the pre-PL mean were included in the PL group.

The tibial tunnels of the enrolled patients were classified into AM and PL groups in the same manner; the tunnel positions were referenced in the anteroposterior and mediolateral planes over the widest portion of the proximal tibia. The mean locations of the anatomic tibial footprint according to previous cadaveric studies[19,21,25,28,35] were as follows: AM (37.3% in anteroposterior, 47.0% in mediolateral) and PL (47.8% in anteroposterior, 51.6% in mediolateral). We defined the mean AM and PL as pre-AM and pre-PL means, respectively (expressed as red and blue stars in Figure 2B). The classification of the AM and PL groups' tibial tunnels proceeded in the same manner as the femoral tunnels.

Surgical Technique and Rehabilitation

A single surgeon (K.H.Y.) performed all ACLRs. Autologous hamstring tendon grafts were harvested from the ipsilateral leg and trimmed to approximately 8 to 9 mm in diameter. The tibial tunnel was created to make an intra-articular orifice on the ACL footprint from the inferomedial side of the tibial tuberosity, using the same incision as that for the hamstring autograft. The remnant fibers were preserved, and the femoral tunnels were created beside the remnant fibers, which resulted in an unequivocal tunnel position among the anatomic footprints. The graft tendon was fixed (1) on the tibial side with a soft tissue washer and screw and with a biodegradable interference screw fitted to the diameter of the tunnel and (2) on the femoral side with an EndoButton CL (Smith & Nephew). The rehabilitation protocol was the same for all patients.

Clinical and Stability Evaluation

The clinical scores and stability function tests were evaluated at every follow-up visit in our outpatient clinic. The clinical scores were the Lysholm, Tegner activity, and IKDC subjective (International Knee Documentation Committee) scores. The stability function tests were the anterior drawer, Lachman test, pivot-shift tests as well as the side-to-side difference in anterior tibial translation on Telos stress radiography at 30° of knee flexion. The anterior translation measurements were categorized into 4 groups: normal (0-2 mm), nearly normal (3-5 mm), abnormal (6-10 mm), and severely abnormal (>10 mm). Two independent investigators performed radiologic measurement on anterior tibial translation to minimize observational bias. The intraclass correlation coefficient for interobserver reliability was >0.8, indicating good reliability.

MRI Evaluation

The ACL graft condition was assessed using MRI (3.0-T Achieva; Philips Medical Systems), with a knee coil

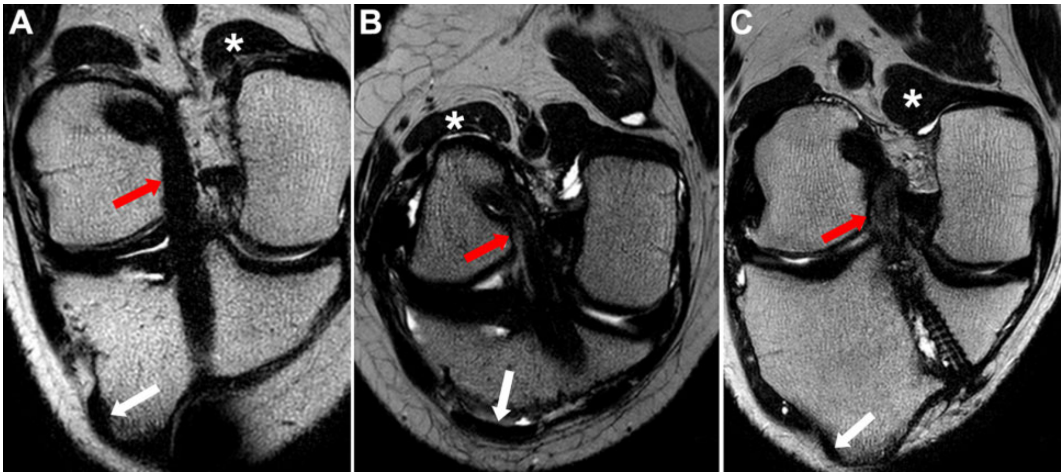

Figure 3. MRI scans after ACL reconstruction: oblique coronal view. White arrow, patellar tendon for low-signal MRI intensity; asterisk, gastrocnemius muscle for intermediate-signal MRI intensity; red arrow, ACL graft. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

preoperatively and at 1 year postoperatively in all patients. The images were taken with the patient positioned in 5° of knee flexion. At 1-year follow-up, graft signal intensity was evaluated and classified according to the protocol of Kanamiya et al[11] based on T2-weighted oblique-coronal images (repetition time, 4194 ms; time echo, 100 ms), which express the ACL fibers in parallel. Low signal intensity was the same as that of the patellar tendon (Figure 3A); intermediate signal intensity was the same as that of the gastrocnemius muscle (Figure 3B); and high signal intensity was greater than intermediate signal intensity (Figure 3C).

Statistical Analysis

When the normality test was simultaneously performed, demographic data, pre- and postoperative IKDC scores, and Lysholm scores showed normality per Kolmogorov-Smirnov, and the rest did not. For the preoperative demographic data, a 1-way ANOVA test (analysis of variance) was used to compare the 4 groups. For the IKDC subjective and Lysholm scores, the same test was used. For the Tegner score, the Kruskal-Wallis test was used. Comparisons of other categorical variables, including the anterior drawer, Lachman, and pivot-shift tests and anterior translation, were performed using the Fisher exact test.

The Wilcoxon signed-rank test was used to compare the preoperative and latest follow-up data within each group. The Fisher exact test was also used to compare the postoperative MRI signal intensity and graft failure among groups. The significance level was set at a $P < .05$ for the Kruskal-Wallis test, 1-way ANOVA test, and Wilcoxon signed-rank test and at $P < .0125$ for the Mann-Whitney test (0.05/4; Bonferroni method). All statistical analyses were conducted using SPSS Statistics for Windows (Version 20; IBM).

RESULTS

The preoperative demographic characteristics of the study patients did not differ significantly among the 4 study groups (Table 1).

Clinical Scores

In all 4 groups, clinical scores improved at the latest follow-up as compared with the preoperative scores ($P \leq .001$ for all). There was no significant difference in any clinical score among the 4 groups at the latest follow-up (Table 2).

Knee Joint Stability

There was no significant difference among the 4 groups in terms of stability of the knee joint, including the anterior drawer, Lachman, and pivot-shift test results and side-to-side differences in anterior tibial translation. The stability test results at the latest follow-up are summarized in Table 3.

MRI Signal Intensity and Graft Failure

There was no significant difference in the postoperative MRI signal intensity of the grafts among the 4 groups ($P = .264$). ACL graft failure did not significantly differ among the 4 groups ($P = .242$) (Table 4).

DISCUSSION

There were no significant differences among the 4 groups investigated in this study. Given the available numbers, we could not conclude that there was a difference as long as the tunnels were located within the anatomic footprints.

A systematic review[17] of the anatomic footprint of the ACL on the tibia and femur reported that the mean length

TABLE 1
Preoperative Demographic Data[a]

	Mean ± SD or No. of Patients[b]				
	AA	AP	PA	PP	*P* Value
Age, y	29.7 ± 12.6	29.9 ± 11.9	28.3 ± 10.8	27.1 ± 10.4	.411[c]
Sex					.609[d]
Male	28	22	24	29	
Female	5	4	5	2	
Injury side					.670[d]
Right	17	17	15	16	
Left	16	9	14	15	
Follow-up, mo	33.1 ± 12.8	39.2 ± 16.6	40.3 ± 13.8	34.2 ± 9.8	.057[c]
Score					
Lysholm	31.5 ± 21.9	33.5 ± 23.6	38.0 ± 18.4	35.8 ± 23.9	.569[c]
Tegner	2.1 ± 1.2	1.8 ± 1.2	1.9 ± 1.1	1.8 ± 1.5	.659[e]
IKDC	41.1 ± 15.2	38.6 ± 13.2	36.2 ± 14.2	37.1 ± 14.2	.555[c]
Test, grade 0/1/2/3					
Anterior draw	2/12/18/0	2/7/16/1	1/7/20/1	0/10/19/2	.764[d]
Lachman	1/11/19/1	1/6/17/2	0/9/17/3	2/5/20/4	.695[d]
Pivot shift	0/14/18/1	1/10/12/3	1/9/16/3	1/6/20/4	.505[d]

[a]IKDC, International Knee Documentation Committee.
[b]For group definitions, see Patient Classification section.
[c]One-way analysis of variance.
[d]Fisher exact test.
[e]Kruskal-Wallis test.

TABLE 2
Clinical Scores at the Preoperative Period and Latest Follow-up[a]

	Mean Score[b]				
	AA	AP	PA	PP	*P* Value[c]
Lysholm score					
Preoperative	31.5	33.5	38	35.8	.637
Latest follow-up	79.9	81.9	78.7	81.3	.418
P value [d]	**≤.001**	**≤.001**	**≤.001**	**≤.001**	
Tegner score					
Preoperative	2.1	1.8	1.9	1.8	.659
Latest follow-up	5.7	6.3	6	6.4	.448
P value[d]	**≤.001**	**≤.001**	**≤.001**	**≤.001**	
IKDC subjective score					
Preoperative	41.1	38.6	36.2	37.1	.569
Latest follow-up	85	88.8	84.5	87	.326
P value[d]	**≤.001**	**≤.001**	**≤.001**	**≤.001**	

[a]Bold *P* values indicate statistically significant difference ($P < .05$). IKDC, International Knee Documentation Committee.
[b]For group definitions, see Patient Classification section.
[c]Kruskal-Wallis test.
[d]Wilcoxon signed-rank test.

of the tibial insertion ranged from 14 mm (Siebold et al[33]) to 29.3 mm (Kopf et al[17]). The area of the tibial and femoral insertions ranged from 114 mm^2 (Siebold et al) to 229 mm^2 (Luites et al[22]) and from 83 mm^2 (Seibold et al) to 197 mm^2 (Ferretti et al[4]), respectively. These are wide enough to make >2 tunnels for ACLR, which would be >50.24 mm^2 in their articular opening areas according to the insertion angle with an 8-mm reamer.

TABLE 3
Results of Stability Tests at the Latest Follow-up[a]

	No. of Patients[b]				
	AA	AP	PA	PP	*P* Value[c]
Anterior drawer test					.675
0	30	21	23	26	
1+	3	5	6	5	
2+	0	0	0	0	
3+	0	0	0	0	
Lachman test					.837
0	25	21	23	25	
1+	7	5	6	4	
2+	1	0	0	2	
3+	0	0	0	0	
Pivot-shift test					.843
0	29	22	23	26	
1+	3	4	5	5	
2+	1	0	1	0	
3+	0	0	0	0	
Anterior translation: STSD, mm					.817
Normal, 0-2	17	12	10	14	
Nearly normal, 3-5	11	8	13	8	
Abnormal, 6-10	5	5	5	7	
Severely abnormal, >10	0	1	1	2	

[a]STSD, side-to-side difference.
[b]For group definitions, see Patient Classification section.
[c]Fisher exact test.

Many surgeons were interested in the relationship between the tunnel positions in ACLR and their effects on biomechanical properties. Udagawa et al[36] suggested that a

TABLE 4
MRI Signal Intensity and Graft Failure by Group[a]

	No. of Patients[b]				
	AA	AP	PA	PP	*P* Value[c]
MRI signal intensity					.264
Low	16	8	18	12	
Intermediate	11	10	8	14	
High	6	8	3	5	
Graft failure	2/33	1/26	5/29	5/31	.242

[a]MRI, magnetic resonance imaging.
[b]For group definitions, see Patient Classification section.
[c]Fisher exact test.

markedly more anteriorly or laterally positioned tibial tunnel can cause an impingement for the anterior or lateral intercondylar notch. Kamath et al[10] suggested that an anterior femoral tunnel placement results in excessive graft tension during flexion, causing loss of knee flexion or stretching of the graft. Carson et al[3] suggested that a posteriorly placed femoral tunnel results in excessive graft tension while the knee is in full extension with laxity in flexion.

Accordingly, many clinical studies have been conducted to evaluate the association between the tunnel positions and their clinical results. Among them, Lee et al[20] reported that different positions of the femoral ACL tunnel cause MRI graft signal changes at postoperative follow-up.

However, as we mentioned, there has been 1 biomechanical study and no comparative clinical study simultaneously considering tibial and femoral tunnel positions. Kato et al[12] conducted a biomechanical study in which the positions in ACLR were divided into 4 groups (AM-AM, PL-PL, Mid-Mid, and PL–High AM); they suggested that the AM-AM group afforded the highest in situ force and the least anterior tibial translation. This is one of the reasons why we hypothesized that the AA group would achieve better clinical scores, stability, and MRI results than the other groups. Another reason is that the AM bundle is nearly isometric among the graft insertions when the knee flexes,[1] which could lead to improved longevity of the ACL graft.

There are several limitations to be taken into consideration. First, this is a retrospective study with a relatively small sample size, which may have resulted in our study lacking sufficient power to detect a difference such that we could rule out the possibility of a type 2 error. The number of patients with ACLR was reduced because many patients had a meniscal repair procedure, which led to a different rehabilitation protocol. Second, the mean AM and PL bundle locations on the tibial and femoral footprints of the previous cadaveric ACL studies may not represent the true centers of the AM and PL bundle footprints of the individuals. Many femoral tunnels were located near the central position, but we could not categorize them into an additional group given the limitations of the statistical techniques and the small sample sizes. If there were enough patients, it could make some difference through dividing the cases into AM, PL, and central groups for the femoral tunnel positions. Third, the remnant-preservation technique was not considered, which led the femoral tunnel to a rather PL position.

CONCLUSION

In the current study, no significant differences in clinical scores, knee joint stability, or graft signal intensity on follow-up MRI were identified between the patients with anteromedially and posterolaterally positioned tunnels.

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