Lateral tenodesis procedures increase lateral compartment pressures more than anterolateral ligament reconstruction, when performed in combination with ACL reconstruction: a pilot biomechanical study

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ABSTRACT

Objectives Given the common occurrence of residual laxity and re-injury post anterior cruciate ligament reconstruction (ACLR), additional anterolateral procedures are increasingly used in combination with an ACLR. Despite the perception that there is a risk of over-constraining the lateral tibiofemoral (LTF) compartment, potentially leading to osteoarthritis, assessment on their effect on intra-articular compartment pressures is still lacking. Our objective was therefore, through a pilot biomechanical study, to compare LTF contact pressures after the most commonly used anterolateral procedures.

Methods A controlled laboratory pilot study was performed using 4 fresh-frozen cadaveric whole lower limbs. Through 0° to 90° of flexion, LTF contact pressures were measured with a Tekscan sensor, located under the lateral meniscus. Knee kinematics were obtained in 3 conditions of rotation (NR: neutral, ER: external and IR: internal rotation) to record the position of the knees for each loading condition. A Motion Analysis system with a coordinate system based on CT scans 3D bone modelling was used. After an ACLR, defined as the reference baseline, 5 anterolateral procedures were compared: anterolateral ligament reconstruction (ALLR), modified Ellison, deep Lemaire, superficial Lemaire and modified MacIntosh procedures. The last 3 procedures were randomised. For each procedure, the graft was fixed in NR at 30° of flexion and with a tension of 20 N.

Results Compared with isolated ACLR, addition of either ALLR or modified Ellison procedure did not increase the overall LTF contact pressure (all $p > 0.05$) through the full range of flexion for the IR condition. Conversely, deep Lemaire, superficial Lemaire and modified MacIntosh procedure (all $p < 0.05$) did increase the overall LTF contact pressure compared with ACLR in IR. No significant difference was observed in ER and NR conditions.

Conclusion This pilot study, comparing the main anterolateral procedures, revealed that addition of either ALLR or modified Ellison procedure did not change the overall contact pressure in the LTF compartment through 0° to 90° of knee flexion. In contrast, the deep and superficial Lemaire, and modified MacIntosh procedures significantly increased overall LTF contact pressures when the knee was internally rotated.

What are the new findings

- Compared with ACLR, anterolateral ligament reconstruction and modified Ellison procedure did not change the overall pressure in the LTF compartment through 0° to 90° of knee flexion.
- In contrast, the deep and superficial Lemaire, and modified MacIntosh procedures significantly increased contact pressures when the knee was internally rotated.
- While these anterolateral procedures most likely do improve rotational control and stability, there is a potential negative effect of increased LTF compartment pressures. This provides a rationale when deciding on the addition of an anterolateral procedure to an ACLR, to choose a procedure in appropriate selected populations.

INTRODUCTION

After anterior cruciate ligament reconstruction (ACLR), approximately 90% of patients achieve normal or near normal knee function.¹ However, 11%–30% still present with recurrent and persistent anterolateral rotational laxity,^{2–4} with a risk of graft failure.⁵ This unsolved issue has led to a renewed interest in extra-articular anterolateral structures, such as the anterolateral ligament (ALL), the iliotibial band (ITB), the anterolateral capsule and the Kaplan fibres (KF),^{6–8} suggesting that an unaddressed anterolateral injury can contribute to residual anterolateral rotational laxity.^{9–10} In this context, combining an ACLR with an anterolateral procedure, such as a lateral extra-articular tenodesis (LET) or an ALL reconstruction (ALLR), has been suggested to offer an advantage in controlling rotation when compared with isolated ACLR.^{11–13}

Despite little evidence in the literature, a prevailing perception is that a combined ACLR with anterolateral procedure has a risk of over-constraining the knee and possibly increasing the risk of osteoarthritis. Based on biomechanical findings,^{14–18} it was hypothesised that the non-isometric behaviour of anterolateral procedures altered the knee kinematics placing the tibia in abnormal external rotation in flexion and reducing maximum

internal rotation, which may predispose to increased load on the cartilage and meniscus in the lateral tibiofemoral (LTF) compartment. High joint contact pressures causing an elevation of cartilage stresses is recognised to be a predictive factor of degenerative changes in vivo.^{19 20} However, only two clinical series have evaluated the long-term outcomes of these combined procedures, and they reported contradictory results.^{21 22} To help resolve the question of whether the addition of an anterolateral procedure to an ACLR increases the load in the lateral tibiofemoral compartment, a direct assessment on the effect of anterolateral procedures on intra-articular compartment pressures is needed. To our knowledge, only one study evaluating LTF pressure after an anterolateral procedure is available which only analysed the modified MacIntosh tenodesis, without assessment of other techniques such as Lemaire,²³ MacIntosh,²⁴ Ellison²⁵ and ALLR.²⁶ Given the complexity of setting up an assessment of LTF contact pressure during knee motion, combined with the challenge of comparing all these procedures together, a pilot study was warranted.

As ALLR is based on the concept of reconstruction of an anatomical structure, we hypothesised that ALLR would not increase the LTF contact pressure as much as the less anatomical LET procedures. The objective of this study was therefore, through a cadaveric pilot study, to compare LTF contact pressures after the most commonly used anterolateral procedures in combination with an ACLR.

MATERIALS AND METHODS

Specimen preparation

A controlled laboratory pilot study was performed using four fresh-frozen cadaveric knees from two half bodies. We used the whole leg and pelvis in order to keep the ITB intact, as well as all of other synergistic bi-articular structures crossing the hip and/or the knee. The specimens were exposed to room temperature for 24 hours prior to the experimentation. The specimens were procured from a tissue bank after approval from the local research ethics committee.

Examination of the knee and an arthroscopy via an antero-medial portal were performed to check the ACL status. None of

the four cadavers had an ACL injury (a positive anterior tibial drawer, a positive pivot shift test or an arthroscopic ACL tear), severe deformities, severe knee osteoarthritis or previous knee surgery.

Experimental set-up and kinematics measurement

The specimen was fixed on a bench to control both pelvic and the femoral movements, with the lower leg allowed to hang free in order to take the knee through a full range of motion (knee extension to full flexion, internal and external rotation).

Kinematic data were obtained to record the position of the knees for each loading condition by using a Motion Analysis 3D optoelectronic system (Vicon, LA, USA). The system consisted of five high-definition Vicon Bonita cameras on tripods operating at 100 Hz. Each knee was prepared with four bi-cortical pins (two for the femur and two for the tibia) placed to avoid soft-tissue impingement (femoral pins between the heads of the quadriceps and tibial pins in the tibial crest). Two retro-reflective markers were fixed to each pin. After pin insertion, a CT scan was performed to register the reference coordinates system using a previously validated imaging protocol.²⁷ Joint centres and bone landmarks were calculated from 3D bone models obtained as defined in the ISB

Figure 1 (A) A Tekscan pressure sensor was inserted into the knee through the lateral capsule and was pulled into the lateral tibiofemoral joint arthroscopically via a suture through an anterior tibial tunnel. (B) The sensor without (left) and with (right) a plastic tape, allowing suture fixation and aiding in arthroscopic placement. (C) Arthroscopic final view of the lateral tibiofemoral compartment showing the sensor location on the lateral tibial plateau under the lateral meniscus. (D) Lateral view showing the entrance of the sensor into the joint through the same incision that was performed for the anterolateral complex transection and the suture anchor fixation.

Figure 2 After obtaining a combined ACL plus anterolateral-deficient knee, joint contact pressure data were recorded from the following six consecutive knee conditions: (1) isolated ACLR (=reference baseline), (2) combined ACLR and ALLR, (3) combined ACLR and modified Ellison procedure, (4) combined ACLR and modified deep Lemaire procedure, (5) combined ACLR and modified superficial Lemaire procedure, (6) combined ACLR and modified MacIntosh procedure. The last three procedures (deep and superficial Lemaire, modified MacIntosh) were randomised. F1: Femoral tunnel position for ALL reconstruction and Lemaire procedures (5 mm posterior and proximal to the femoral epicondyle). F2: Femoral tunnel position for modified MacIntosh procedure (70 mm posterior and proximal to the femoral epicondyle). T1: Tibial tunnel position for ALL reconstruction (equidistant from the centre of GT and the anterior margin of the fibular head and 10 mm distal to the joint line). ACLR, anterior cruciate ligament reconstruction; ALL, anterolateral ligament; GT, Gerdy's tubercle; KF, Kaplan fibres; LCL, lateral collateral ligament.

Figure 3 Contact pressure (peak and mean pressure) from 0° to 90° of flexion, when the knee is internally rotated between the different knee conditions. ACLR, anterior cruciate ligament reconstruction; ALLR, anterolateral ligament reconstruction.

(International Society of Biomechanics) conventions and by Grood and Suntay.^{28 29} After processing the kinematics using Visual3D software, the data were filtered (Butterworth filter of order 4 with a cut-off frequency of 6 Hz). The kinematics were interpolated to obtain values for each degree of knee flexion from 0° to 90°. In a preliminary work, this tracking system has been reported to have a translational accuracy of less than 0.04 mm and a rotational accuracy of less than 0.2°.³⁰

Measurement of lateral tibiofemoral contact pressures

Contact stresses of the lateral tibial plateau surface were recorded in real time (100 Hz) using a pressure mapping electronic sensor (model 6900N; Tekscan, MA)^{26 31–34} (figure 1) with a total surface area of 14 mm² and resolution of 62 sensels/cm². Calibration and equilibration were performed as advised by the manufacturer. A new sensor was used for each knee to avoid cumulative degradation.

Plastic tape was attached to the top and bottom faces of the Tekscan sensor. This allowed a tab to be formed for suture fixation and aiding in arthroscopic placement. The construct was a thickness of 0.2 mm and a preliminary control was performed to ensure that the tape did not change the sensor readings.

A passing suture was fixed to the tab and the sensor was introduced to the knee through a 10 mm longitudinal incision in the capsule inferior to the lateral meniscus. As the objective was to assess the reconstruction on a combined ACL plus anterolateral-deficient knee, we used the same surgical approach performed for the anterolateral complex transection. This allowed placement of the sensor in the LTF compartment while minimising the disruption to the meniscocapsular attachments. A 2 mm drill hole was made into the anteromedial part of the lateral tibial plateau using an arthroscopic drill guide. The position was close to the anterior root of the lateral meniscus, at the anterior edge

of the load-bearing area unlikely to affect the contact pressure readings. The passing suture was retrieved through the drill hole facilitating correct positioning of the sensor underneath the lateral meniscus. The sensor could now be fixed anteriorly using a cortical button and laterally using two suture anchors on the edge of the tibia.

Surgical techniques and conditions

Surgery was performed by a single experienced orthopaedic surgeon in all specimens. Six conditions were successively analysed for each knee (figure 2). Following arthroscopic ACL transection, the anterolateral complex (ALC) transection was then performed. This included transection of the ALL, anterolateral capsule (figure 1D) and proximal and distal KF, without damaging the ITB by retracting it anteriorly. After obtaining a combined ACL plus anterolateral-deficient knee, an ACLR was performed with a quadrupled hamstring autograft (semitendinosus) fixed using adjustable cortical suspensory fixation in the femur and tibia (Graftlink system; Arthrex, Florida, USA) (*Condition 1: isolated ACLR*).

After ACLR, defined as the reference baseline, five anterolateral extra-articular procedures were performed on each knee: ALLR, modified Ellison, deep Lemaire, superficial Lemaire and modified MacIntosh procedures. To allow comparison between procedures, the graft was always fixed in the same condition: in neutral rotation at 30° of flexion and with 20 Nm of applied tension.^{35–36}

- ▶ *Condition 2: A combined ACLR and ALLR.* The ALLR was performed with a free gracilis graft passing under the ITB and over the lateral collateral ligament (LCL), according to Chahla technique.³⁷ The graft was passed into closed-socket tunnels and fixed with interference screws. The tibial tunnel was located equidistant from the centre of Gerdy's tubercle (GT) and the anterior margin of the fibular head and 10 mm distal to the joint line.^{38–39} The femoral socket was located 5 mm proximal and posterior to the LCL's femoral insertion.^{38–40}
- ▶ *Condition 3: A combined ACLR and modified Ellison procedure* as described by Devitt *et al*⁴¹ was performed. It consisted of a 15 mm wide central strip of ITB detached distally by performing a thin GT osteotomy. This strip was passed deep to the LCL and the bone fixed back to the GT bed. Fixation was with 3.5 mm suture anchors reinforced with a staple. The ITB defect was then closed.
- ▶ *Condition 4: A combined ACLR and modified deep Lemaire procedure* was performed, using a 15 × 100 mm central strip of the ITB passed under the LCL and fixed in the same tunnel as the ALLR with an interference screw.
- ▶ *Condition 5: A combined ACLR and modified superficial Lemaire* was performed using the same graft and the same femoral fixation site as condition 4, but with the graft positioned over the LCL.
- ▶ *Condition 6: A combined ACLR and modified MacIntosh* was performed by using a 15 × 150 mm central strip of ITB, passed underneath the LCL and through a further closed-socket tunnel 70 mm proximal to femoral epicondyle at the insertion of the lateral intermuscular septum, and fixed with an interference screw.⁴²

Testing protocol

Joint contact pressure data were recorded for all six consecutive knee conditions. For reasons of feasibility and ITB preservation, only the last three procedures were randomised to avoid any bias due to deterioration of the tissue. Peak and mean contact

pressure (MPa) were analysed for each loading condition. The five anterolateral procedures were compared for each tibial rotation, with reference to the isolated ACLR state.

Knee kinematics and LTF contact pressure were recorded from three cycles through 0° to 90° of passive knee flexion, with three conditions of rotation: neutral (NR), external (ER) and internal rotation (IR). The mean of the three cycles was used. For NR with unconstrained tibial rotation, the foot was placed in NR and the tibia in its anatomical position with respect to the femur. IR and ER were performed with a rotation torque applied to the tibia, provided by a dynamometric torque rig placed at the tibiofibular mortise, triggering at 5 Nm. We used the same rig as had previously been validated in preliminary work.³⁰

Statistical analysis

All statistical analyses were performed using SPSS Statistic Version 23 software, with a significance level set at $p < 0.05$.

Peak and mean contact pressure were compared for every condition and for each loading condition to the ACLR state, which was defined as the reference baseline.

Two-way repeated-measures analyses of variance (ANOVAs) were used to compare dependent variables (peak and mean LTF contact pressures) across the two independent variables: flexion angle (from 0° to 90° of knee flexion) and state of the knee (six knee conditions). This was performed for the three conditions of tibia rotation (NR, IR and ER). Overall comparison of LTF contact pressures was performed through 0° to 90° of flexion, and then readings taken at four flexion angles (0°, 30°, 60° and 90°) for further direct comparison. The ACLR state was defined as the reference baseline. When differences across the test conditions were found, pairwise t-tests and Bonferroni corrections were applied to correct for multiple comparisons.

Assuming an alpha risk at 0.05, a power at 0.80 and a moderate effect size ($f = 0.4$), the appropriate sample size for an ANOVA with six repeated measures was 4 (G^*Power , V.3.1).

RESULTS

Internal tibial rotation

Contact pressure outcomes related to knee flexion for IR condition are shown in figure 3. Compared with isolated ACLR, addition of either ALLR or modified Ellison procedure did not increase the overall LTF peak contact pressure (ALLR: $p = 0.089$; modified Ellison: $p = 0.065$) through the full range of flexion (0° to 90°). This was similar for the overall mean LTF contact pressure (ALLR: $p = 0.197$; modified Ellison: $p = 0.290$) compared with isolated ACLR. Conversely, superficial and deep Lemaire, and modified MacIntosh tenodeses all increased the overall LTF peak pressure (superficial Lemaire: $p = 0.006$; deep Lemaire: $p = 0.001$, modified MacIntosh: $p = 0.049$) and the overall LTF mean contact pressure (superficial Lemaire: $p = 0.002$; deep Lemaire: $p = 0.011$; modified MacIntosh: $p = 0.027$) compared with isolated ACLR.

Comparisons of mean contact pressure at specific flexion angle values and across the different procedures are shown in table 1. At 30° and 60° of flexion, superficial and deep Lemaire increased the LFP mean contact pressure (all $p < 0.05$), while ALLR, modified Ellison and modified MacIntosh did not induce a contact pressure change (all $p > 0.05$). At 90° of flexion, only the superficial Lemaire led to a higher contact pressure level ($p = 0.03$). In full extension, the addition of an anterolateral procedure did not change the contact pressure compared with ACLR.

Table 1 Comparisons of mean contact pressure in internal rotation at specific flexion angle value (0°, 30°, 60° and 90°) between isolated ACLR and combined ACLR with an anterolateral procedure

Δ LTF mean contact pressure compared with isolated ACLR in MPa (p value)								
	0°		30°		60°		90°	
ACLR+ALLR	-0.04	0.724	-0.09	0.396	+0.22	0.258	+0.12	0.271
ACLR+Ellison	+0.19	0.505	+0.19	0.237	-0.05	0.367	+0.01	0.875
ACLR+MacIntosh	-0.19	0.630	+0.69	0.107	+0.24	0.132	+0.08	0.385
ACLR+superficial Lemaire	-0.66	0.278	+0.86*	0.003	+0.61*	0.006	+0.47*	0.030
ACLR+deep Lemaire	+0.62	0.120	+1.11*	0.001	+0.71*	0.005	+0.41	0.106

*p<0.05.

ACLR, anterior cruciate ligament reconstruction; ALLR, anterolateral ligament reconstruction; LTF, lateral tibiofemoral compartment.

Figure 4 Contact pressure (peak and mean pressure) from 0° to 90° of flexion, when the knee is in neutral rotation between the different knee conditions. ACLR, anterior cruciate ligament reconstruction; ALLR, anterolateral ligament reconstruction.

Figure 5 Contact pressure (peak and mean pressure) from 0° to 90° of flexion, when the knee is externally rotated between the different knee conditions. ACLR, anterior cruciate ligament reconstruction; ALLR, anterolateral ligament reconstruction.

Neutral tibial rotation

Contact pressure outcomes related to knee flexion for NR condition are shown in figure 4. When the anterolateral procedure was performed in combination with an ACLR, no change of the overall LTF peak pressure (ALLR: $p=0.104$; modified Ellison: $p=0.402$; modified MacIntosh: $p=0.064$; superficial Lemaire: $p=0.650$; deep Lemaire: $p=0.151$) or of the mean contact pressure (ALLR: $p=0.138$; modified Ellison: $p=0.306$; modified MacIntosh: $p=0.094$; superficial Lemaire: $p=0.115$; deep Lemaire: $p=0.085$) through the full range of flexion was observed compared with isolated ACLR.

External tibial rotation

Contact pressure data when the knee is externally rotated are shown in figure 5. Similar to NR, there was no difference between

isolated ACLR and combined ACLR with an anterolateral procedure, for the overall LTF peak pressure (ALLR: $p=0.440$; modified Ellison: $p=0.376$; modified MacIntosh: $p=0.107$; superficial Lemaire: $p=0.206$; deep Lemaire: $p=0.485$) and for the mean contact pressure (ALLR: $p=0.798$; modified Ellison: $p=0.272$; modified MacIntosh: $p=0.143$; superficial Lemaire: $p=0.210$; deep Lemaire: $p=0.127$).

DISCUSSION

This pilot study is the first to our knowledge to provide a direct comparison of the LTF contact pressure between commonly used anterolateral procedures. This pressure assessment was performed in a whole leg, keeping all bi-articular structures intact, maintaining their potential effect on knee mechanical behaviour, and was coupled with kinematic measurements to

record the position of the knees for each loading condition. The main finding was that the addition of either ALLR or modified Ellison procedure did not change the overall contact pressure from 0° to 90° of flexion in the LTF compartment. In contrast, the deep and superficial Lemaire, and modified MacIntosh procedures significantly led to high level of LTF contact pressure when the knee was internally rotated.

One of the factors that has restricted the uptake of antero-lateral procedures is the fear of over-constraining the LTF compartment, potentially leading to cartilage and meniscal wear. Analysis of the clinical series of combined ACLR and anterolateral procedures reveals no clear evidence of increased osteoarthritis. As far we are aware, there are only a few studies reporting on the long-term effect of combined extra-articular and intra-articular procedures,^{21 43} and less comparing isolated ALCR and combined surgery.^{22 42} The rate of established osteoarthritis after a combined ACLR and LET varies between 17.5% at 7 years²¹ and 27% at 25 years,⁴³ and appears to be more related to the state of the medial meniscus and the femoral articular surface at the index surgery than the addition of anterolateral procedures.⁴⁴ In a retrospective comparative study with 25 years of follow-up, Ferretti *et al*²² reported less arthritic changes in the combined procedure group. A recent systematic review suggests that the addition of a LET to ACLR does not result in an increased rate of osteoarthritis within the knee.⁴²

Therefore, as explained by Ferretti,⁴⁵ there has been a discrepancy between accepted recommendations and clinical findings on this issue. Most recommendations, such as those of the American Orthopaedic Society for Sports Medicine consensus meeting in 1989, are based on expert opinion.⁴⁵ A randomised controlled trial is needed before establishing a clear recommendation. It would certainly be interesting to investigate whether or not performing these procedures on patients with lateral compartment meniscal or chondral pathology has worse outcomes than patients without such pathology, due to the over-constraint enhancing the potential for osteoarthritis already created by the lateral compartment pathology. If this is the case, then it could influence surgeons' indications to use this procedure, although such information would require longer-term clinical studies.

Despite the lack of *in vivo* studies in the literature, several *in vitro* biomechanical studies have demonstrated that antero-lateral procedures, especially an ITB tenodesis, can induce over-constraint of the knee by decreasing internal rotation.^{14–18} Among the variety of anterolateral procedures, there must be a biomechanical difference between each of them.

The effect of knee flexion angle at the time of fixation does influence subsequent knee kinematics.^{35 36 46} However, in the present study, it was controlled at 30° of flexion in neutral rotation for all conditions.

The difference in geometry between the fixation points appears to be crucial. It could explain the differential in LTF contact pressures observed between the ALLR and Lemaire procedures.⁴⁶ While there is no difference in the femoral insertion point between both techniques (they both use a tunnel positioned posterior and proximal to the femoral epicondyle), there is a difference in their tibial attachment sites. The tibial positioning of the Lemaire procedures is located at the level of the GT, which is therefore anterior (approximately 18 to 20 mm) from that of the ALLR. Thus, the strength of resistance to internal rotation of the tibia will be greater for the Lemaire procedures than for the ALLR, inducing a higher level of contact pressure by tightening the LTF compartment.

Comparison between superficial and deep Lemaire showed that passing the graft over the LCL induced higher LTF contact

pressure level at 90° of flexion. One hypothesis could be that in flexion, the superficial graft has to travel over the epicondyle which is a longer distance than a path under the LCL, which is closer to the bone. Conversely, passing the graft under the LCL creates a pulley effect, mainly in extension. Therefore, the deep graft would be expected to probably be tighter in extension and the superficial graft tighter in flexion, over-constraining more the LTF compartment.

The modified Ellison technique did not over-constrain the knee. Devitt *et al*,⁴¹ through a biomechanical study, demonstrated that a modified Ellison reconstruction did not result in over-constraint to isolated IR (except at 30° of knee flexion) and restored kinematics close to the intact state. The explanation is likely that the lack of femoral attachment increases the range of variation of the graft length, making this procedure a less rigid system.

Some inherent limitations in this study should be noted. The small size of the sample analysed (four knees) means that this study should be seen in the context of being a pilot study. Although repeated surgeries on the same knee may result in altered tissue properties, this is the only method to ensure a direct comparison between procedures. We tried to minimise this limitation by using a randomisation process. As with every biomechanical study, it is a 'time zero' assessment, which does not evaluate the effects of soft-tissue healing and rehabilitation on tibiofemoral joint load. Although all the bi-articular structures were conserved, the study only measured the static effects of knee load, with no consideration of the active effects of dynamic stabilisers such as the ITB, the quadriceps, the hamstring and the calf muscle groups. This *in vitro* study may have generated lower contact stresses compared with those induced by load-bearing activity.³⁴ Based on previous work,²⁶ we deliberately chose a relatively low tibiofemoral joint load in order to clearly discern the change on the LTF contact pressure induced among the five anterolateral procedures studied. We reported a maximal change of 0.71 MPa, between the conditions studied, which is relatively small compared with the *in vivo* condition, such as sporting activities. Therefore, it may be speculated that the identified changes were subtle and may not be significant in a clinical setting with a fully loaded knee.

CONCLUSION

This pilot study, comparing the five main anterolateral procedures, revealed that addition of either ALLR or modified Ellison procedure did not change the overall contact pressure in the LTF compartment through 0° to 90° of knee flexion. In contrast, the deep and superficial Lemaire, and modified MacIntosh procedures significantly increased overall LTF contact pressures when the knee was internally rotated.

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