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Research article

The utility of dual-energy CT collagen material decomposition technique for the visualization of tendon grafts after knee ligament reconstruction

Ji Young Jeon, Sheen-Woo Lee*, Yu Mi Jeong, Sunghyun Yu

Department of Radiology, Gil Medical Center, Gachon University College of Medicine, 21 Namdong-daero, 774beon-gil, Namdong-gu, Incheon 21565, Republic of Korea

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ABSTRACT

Objective: The purpose of this article is to assess whether dual-energy CT (DECT) collagen material decomposition technique could reliably depict graft integrity in patients with knee ligament reconstruction.

Methods: Seventy patients (mean age, 29.8 years; age range, 15–57 years; 61 men, 9 women) who underwent knee DECT, from June 2016 to January 2018, after knee ligament reconstruction were included in our study. A total of 92 intact tendon grafts (autograft, n = 37; allograft, n = 50), confirmed by MRI and clinical assessment or second-look arthroscopy of the operated knee, were evaluated. The type and number of reconstructed ligaments were as follows: anterior cruciate ligament (ACL) (n = 30), posterior cruciate ligament (PCL) (n = 20), medial collateral ligament (MCL) (n = 12), lateral collateral ligament (LCL) (n = 10), posterolateral ligamentous complex (PLC) (n = 7), anterolateral ligament (ALL) (n = 6), and medial patellofemoral ligament (MPFL) (n = 7). All DECT tendon-specific color mapping images were analyzed by two radiologists independently. Each reconstructed ligament was divided into proximal, middle, and distal portion and rated separately using a three-point scale (0 = absent 'dual-energy color staining'; 1 = partial 'dual-energy color staining'; 2 = full 'dual-energy color staining').

Results: The mean of total visualization scores of reconstructed ligaments were 5 or more out of 6 points (PCL: 5.0 ± 0.8; MCL: 5.4 ± 0.7; LCL: 5.5 ± 0.5; PLC: 5.4 ± 1.0; ALL: 5.3 ± 0.6; MPFL: 5.8 ± 0.5), except for ACL (4.3 ± 1.7). No significant difference was observed in the mean of total visualization scores between the autografts and allografts ($p > 0.05$). The frequency of the score 0 was greater than 10% for the ACL group (15.7%), while less than 5% or 0% for the other groups. Overall, substantial to almost perfect interobserver agreement (range 0.71–0.93) was found for all types of ligaments.

Conclusion: DECT collagen material decomposition technique could be a valuable tool to qualitatively display tendon grafts in the patients with knee ligament reconstruction, but more caution would be needed to assess ACL graft.

1. Introduction

As more traffic accidents occur and traumatic injuries related to strenuous sports or work activities increase, the incidence of ligament tear of the knee has also been increasing. Arthroscopic ligament reconstruction is the modality of choice for high-grade ligament tear of the knee. Today, almost all ligament reconstruction of knee, especially ACL, uses tendon grafts. An autograft from the patient himself or an allograft from a corpse donor can be used. Direct ligament sutures and grafting with synthetic materials are no longer performed [1–3]. While MRI is the imaging reference standard for examining soft tissue structures of the knee, dual-energy CT (DECT) using a three-material collagen decomposition algorithm can improve the soft-tissue characterization of the supporting structures of joints such as ligaments, menisci and tendons. After Johnson et al. initially showed the feasibility of a differentiation of collagen from surrounding tissues using DECT [4], a number of studies have reported the DECT's ability to depict tendons and ligaments in the ankle, wrist, hand, foot and knee region [5–9]. However, there are few studies on the utilization of DECT in the evaluation of reconstructed ligaments as a postoperative imaging tool. Thus, the purpose of our study was to evaluate whether DECT collagen material decomposition technique could reliably depict graft integrity

Abbreviations: DECT, dual-energy CT; ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; MCL, medial collateral ligament; LCL, lateral collateral ligament; PLC, posterolateral ligamentous complex; ALL, anterolateral ligament; MPFL, medial patellofemoral ligament

* Corresponding author at: Department of Radiology, Gil Medical Center, Gachon University College of Medicine, 21, Namdong-daero, 774beon-gil, Namdong-gu, Incheon 21565, Republic of Korea.

E-mail address: leesw1@gilhospital.com (S.-W. Lee).

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in patients with knee ligament reconstruction.

2. Materials and methods

2.1. Patients

This retrospective study was approved by our institutional review board, and the requirement for informed consent was waived. A database search of the period from June 2016 to January 2018 identified 103 patients who underwent DECT examination after knee ligament reconstruction with tendon graft. Among them, 5 patients were excluded because the DECT were obtained during the early postoperative period (within 7 days) and there were no further postoperative DECT scans performed. To select the patients with intact tendon grafts, four patients with torn grafts (partial or complete) on postoperative knee MRI, two patients suspected of graft tear in clinical evaluation (e.g., positive stress test) performed by a board-certified orthopedic surgeon despite normal MRI finding, and two patients with torn grafts confirmed in second-look arthroscopy were excluded. Finally, a total of 70 patients (mean age, 29.8 years; age range, 15–57 years; 61 men, 9 women) were included in our study. Since there were cases that more than one ligament were reconstructed on one knee, a total of 92 intact tendon grafts were included in the 70 DECT examinations (Fig. 1). The type and number of reconstructed ligaments were as follows: anterior cruciate ligament (ACL) (n = 30), posterior cruciate ligament (PCL) (n = 20), medial collateral ligament (MCL) (n = 12), lateral collateral ligament (LCL) (n = 10), posterolateral ligamentous complex (PLC) (n = 7), anterolateral ligament (ALL) (n = 6), and medial patellofemoral ligament (MPFL) (n = 7). Of these, 37 were autografts and 50 were allografts.

2.2. DECT examinations

The mean time between operation to postoperative DECT was 17 weeks (range, 6—38 weeks). The mean time between postoperative DECT to follow-up MRI (excluding MR images taken immediately after operation) was 8 weeks (range, 0—21 weeks).

All CT examinations were performed with a dual-source CT scanner (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany) using a dual-energy mode. In this mode, the two X-ray tubes operated at 80 kV and 140 kV, acquiring two data sets simultaneously. The quality reference mAs were 425 and 100 for the 80 and 140 kV beam, with a real-time automatic tube current modulation software (CAREDose 4D, Siemens Healthcare) turned on. Scans were acquired in 40 x 0.6 mm detector collimation, 0.5 s rotation time, 0.7 helical pitch, 0.75 mm section thickness, 0.5 mm increment. The volume CT dose index (CTDIvol) was 14.05 mGy for a standard sized patient. Conventional linearly blended, virtual 120-kV axial, coronal, and oblique sagittal (i.e., parallel to the lateral femoral condyle as used routinely in knee MRI) planes (thickness: 2 mm; increment: 2 mm; sharp B70 kernel) were obtained by using iterative reconstruction (SAFIRE [Sinogram Affirmed Iterative Reconstruction]) for routine knee CT reading.

2.3. DECT Post processing

For DE-specific analysis of collagen, axial images were reconstructed with a section thickness of 2 mm, increment of 2 mm using the Q34 s dual-energy kernel. Post-processing was conducted on a multimodality workstation (Syngo MMWP, VE40A, Siemens Healthcare) by using the dedicated dual-energy tendon application. This software uses a three-material decomposition (collagen, fat, and soft tissue) to differentiate tendon and ligament from the surrounding soft tissue and color code it for visualization. These color-coded overlay maps were fused onto the standard gray-scale CT images in axial, coronal and oblique sagittal orientations (thickness, 2 mm; increment, 2 mm) and sent to the picture archiving and communication system.

2.4. DECT image evaluation

All images were displayed digitally on monitors with a picture archiving and communication system (PACS) software (INFINITT Healthcare, Korea). Two radiologists (SHY and JYJ; 2 and 10 years of experience in musculoskeletal radiology, respectively) visually analyzed color-coded DECT images independently in a randomized order. The readers were aware of the operated ligament for assessment, but blinded to the other clinical information such as patient sex and age. In accordance with our clinical routine, reviewers were free to choose the appropriate planes— axial, sagittal, or coronal and allowed to modify window width and level.

The reconstructed ligaments were interpreted by using a visual assessment regarding the graft contour and continuity. The pattern and density of color-coding in the patellar tendon was used as the reference standard, since the patellar tendon has been reported as the most clearly displayed collagenous structure in the knee DECT imaging [8]. The interpretation was performed on a per-segment basis. Each tendon graft was divided into proximal, middle, and distal portion and rated separately on a three-point scale as follows : 0 = absent 'dual-energy color staining'; 1 = partial 'dual-energy color staining'; 2 = full 'dual-energy color staining' in the graft (Figs. 2–5). Care should be taken in interpreting the color staining loss around the metal screws for graft fixation, because this could be due to metal artifact (Fig. 6).

The total visualization score was obtained by adding up all the

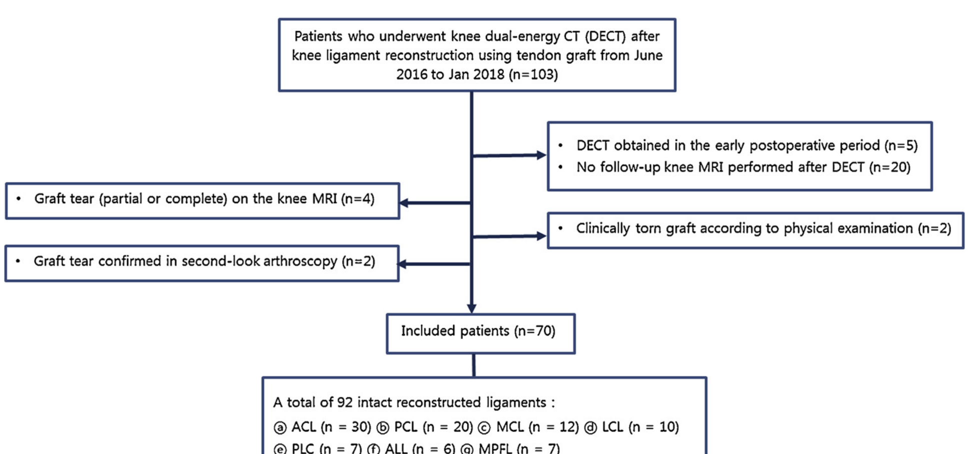

Fig. 1. Flowchart of our study population.

Fig. 2. A 28-year-old male who underwent right anterior cruciate ligament (ACL) reconstruction using tibialis anterior allograft. Dual-energy CT (DECT) and MRI performed 30 weeks after surgery. The reconstructed ACL was clinically intact confirmed by physical examination, including negative Lachman, pivot shift and anterior drawer test. (A) Oblique sagittal T2-weighted (TR/TE, 5250/66) MRI of the right knee showed the intact ACL graft. (B) Oblique sagittal DECT tendon-specific color image demonstrated full 'dual-energy color staining' in the proximal, middle, and distal portion of the ACL graft (score 2).

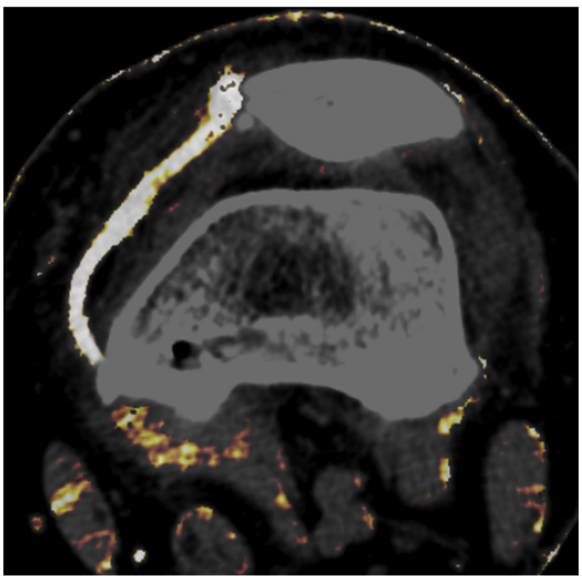

Fig. 3. A 31-year-old male who underwent left medial patellofemoral ligament (MPFL) reconstruction using autohamstring tendon graft. Dual-energy CT (DECT) was performed at 15 weeks after surgery. The follow-up MRI performed 8 weeks after DECT showed the intact MPFL graft. Axial DECT tendon-specific color image demonstrated full 'dual-energy color staining' in the entire MPFL graft (score 2).

scores of the proximal, middle, and distal portion of graft. We also evaluated the frequencies of visualization scores 1–3 for each group. Since the reconstructed ligaments were divided into three parts and scored, the denominators were calculated by multiplying the number of ligaments by three. Using these as denominators, the percentage of visualization scores 0, 1, and 2 were calculated in each ligament group.

2.5. MR image evaluation

A 3-T imaging unit (Skyra, Siemens Healthcare, Forchheim, Germany) equipped with a dedicated knee coil was used to obtain the postoperative MR images. The standard knee MR protocol included the following sequences: (1) coronal T2-weighted turbo spin-echo (TSE), (2) oblique sagittal T2-weighted TSE with/without fat-suppression, (3) oblique sagittal T1-weighted TSE, (4) axial proton density (PD)-weighted TSE with fat-suppression, and (5) coronal fat-suppressed PD-weighted TSE.

A board-certified radiologist (S.W.L with 15 years of experience) who was blinded to the nature of this study and DECT information checked the postoperative MR images to determine the graft integrity. If regarded as a partially or completely torn graft on the follow-up knee MRI, it was excluded in this study. Normal tendon grafts appear as low signal intensity on T1-weighted images and fluid-sensitive sequences during the first two months after surgery. Then, during the period between two months and 1.5–2 years after reconstruction, a process called "ligamentization" occurs and grafts show moderate high signal intensity on T1-weighted images and fluid-sensitive sequences. After 1.5–2 years, grafts generally have low signal intensity on T1-weighted and fluid-sensitive images again, with possible areas of intermediate signal [1,3]. Furthermore, well-preserved continuation and taut orientation was a staple for normal grafts [10].

2.6. Statistical analysis

Continuous variables were presented as mean values with standard deviation. In all ligament groups, differences in total visualization scores between allografts and autografts were compared using the Mann Whitney *U* test Interobserver agreement for visual evaluation of DECT images was obtained by using k statistics. A k value of 0.00–0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80, or 0.81–1.00, indicated slight, fair, moderate, substantial, or almost perfect agreement, respectively [11]. Analyses were performed by using statistical software (SPSS Statistics for Windows version 21, IBM Inc., New York, USA) A P value of 0.05 or less was considered indicative of a statistically significant difference.

3. Results

The mean of total visualization scores of reconstructed ligaments were 5 or more out of 6 points (PCL: 5.0 ± 0.8; MCL: 5.4 ± 0.7; LCL: 5.5 ± 0.5; PLC: 5.4 ± 1.0; ALL: 5.3 ± 0.6; MPFL: 5.8 ± 0.5), except for ACL (4.3 ± 1.7). In all ligament groups, no significant differences were observed in the mean of total visualization scores between the autografts and allografts ($p > 0.05$) (Table 1).

The frequency of the score 0 was greater than 10% for the ACL group (15.7% [14/90]), while less than 5% or 0% for the other groups (PCL: 4.7% [3/60]; PLC: 4.7% [1/21]; MCL, LCL, ALL and MPFL: 0%) (Table 2).

In all types of ligaments, the k values showed substantial to almost perfect interrater agreement (0.71 for ACL; 0.81 for PCL; 0.92 for MCL; 0.84 for LCL; 0.72 for PLC; 0.78 for ALL; and 0.93 for MPFL) for analyzing visualization score at DECT imaging.

4. Discussion

The results of our study show DECT collagen material decomposition could be a valuable tool to qualitatively display various reconstructed ligaments—regardless of autograft or allograft — of the knee with good interrater agreement. However, more caution would be

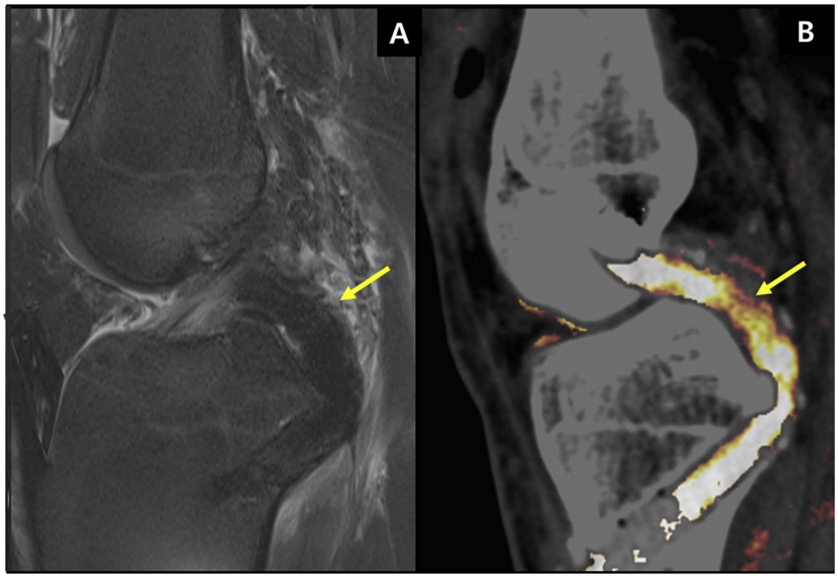

Fig. 4. A 43-year-old male who underwent left posterior cruciate ligament (PCL) reconstruction using Achilles tendon allograft. Dual-energy CT (DECT) and MRI was performed at 20 weeks after surgery. The reconstructed PCL was clinically intact confirmed by physical examination such as posterior drawer test. (A) Oblique sagittal fat-suppressed T2-weighted (TR/TE, 3210/76) MRI of the left knee showed the intact PCL graft. (B) However, on the Oblique sagittal DECT tendon-specific color image, partial 'dual-energy color staining' (score 1) was revealed in the middle portion of the PCL graft (arrow).

needed for evaluating reconstructed ACL using collagen-specific color mapping images because the incidence of insufficient 'dual-energy color staining' (less than score 1) in normal ACL graft (Fig. 5) was rather higher than in other normal ligament grafts.

DECT can be used to differentiate soft-tissue collagenous structures (ligaments and tendons). Tendons and ligaments are made up of elongated fibrils of type 1 collagen, elastin, proteoglycans, glycosaminoglycans, and glycoproteins [12]. Collagen's specific dual-energy index values allow collagen to be decomposed from the surrounding tissue, presumably secondary to its densely packed nature and side chains of hydroxylysine and hydroxyproline [4,13,14]. On a multimodality workstation using a three-material decomposition algorithm (collagen, fat, and soft tissue), they can be color-coded and fused to standard gray-scale CT images to help with anatomic localization and detection of pathologic conditions. A number of studies have reported on DECT's ability to characterize collagenous structures.

There have been various studies on ability of using DECT to visualize collagenous structures. Sun et al (2008) found that in DECT imaging of 24 knees, while some knee ligaments (ACL, PCL, patellar ligament, LCL) were clearly visualized, while others (MCL, transversal ligaments, oblique popliteal ligament) were not satisfactorily displayed for diagnostic assessment [8]. In an ex vivo study by Fickert et al, the delineation of the ACL was equally capable in both DECT and MRI [6]. Further, Deng et al. reported that DECT produced superior images when compared with conventional CT and were useful in visualizing tendons of the hands and feet, such as flexor pollicis longus tendon, flexor digitorum superficialis/profundus tendon, Achilles tendon, extensor halluces longus tendon, and extensor digitorum longus tendon, etc [7].

In addition to providing enhanced anatomical information of tendons and ligaments, DECT could help diagnose pathologic conditions of these collagenous structures. Persson et al (2008) found that DECT adequately assessed ligamentous injury secondary to penetrating wound injuries of the wrist and ankle in postmortem subjects [9]. Also, there were a few case reports that DECT using a collagen material decomposition application was able to be used to detect and diagnose Achilles tendon tear and plantar plate tear missed with conventional CT [5,15]. Recent studies have focused on identification of ACL injuries. Fickert et al. showed that DECT could be a possible substitute to MRI in the detection of iatrogenically induced ACL injuries in a porcine model [6]. Peltola et al. demonstrated DECT was a usable method with favorable sensitivity and specificity to evaluate ACL in acute knee trauma patients [16]. Furthermore, Glazebrook et al. found that an oblique sagittal plane angled to the ACL provided the best reconstruction and demonstrated high accuracy and interobserver agreement on DECT images [17].

Here, we have tried a first of its kind investigation into the role of DECT in visualizing the various reconstructed ligaments of the knee and obtained slightly different results from previous DECT studies with unoperated knee ligaments. Despite using an oblique sagittal plane, delineation of ACL graft was not as satisfactory as other ligament grafts, unlike previous studies reported that ACL was well displayed on DECT [6,8,17]. Thus, it needed to be kept in mind that reconstructed ACL

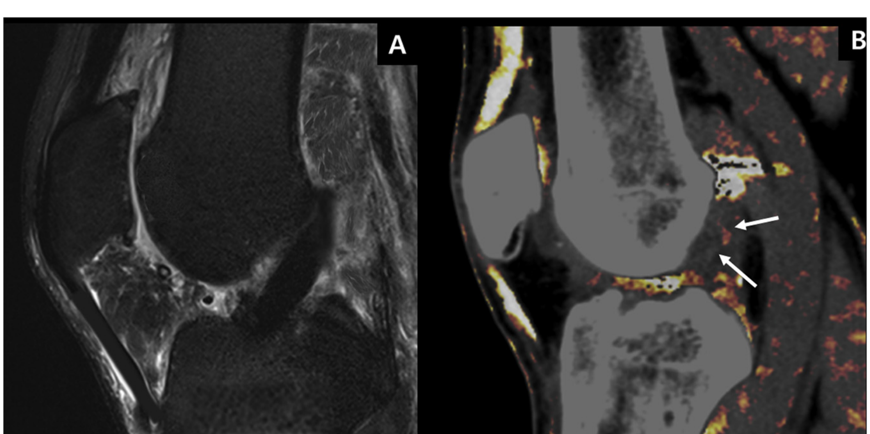

Fig. 5. A 52-year-old male who underwent right anterior cruciate ligament (ACL) reconstruction using Achilles tendon allograft. Dual-energy CT (DECT) performed 16 weeks after surgery and MRI performed 24 weeks after surgery. The reconstructed ACL was clinically intact confirmed by physical examination, including negative Lachman, pivot shift and anterior drawer test. (A) Oblique sagittal fat-suppressed T2-weighted (TR/TE, 5720/67) MRI of the right knee showed the intact ACL graft. (B) However, oblique sagittal DECT tendon-specific color image demonstrated absent 'dual-energy color staining' in the middle to distal portion (arrows) of the ACL graft (score 0).

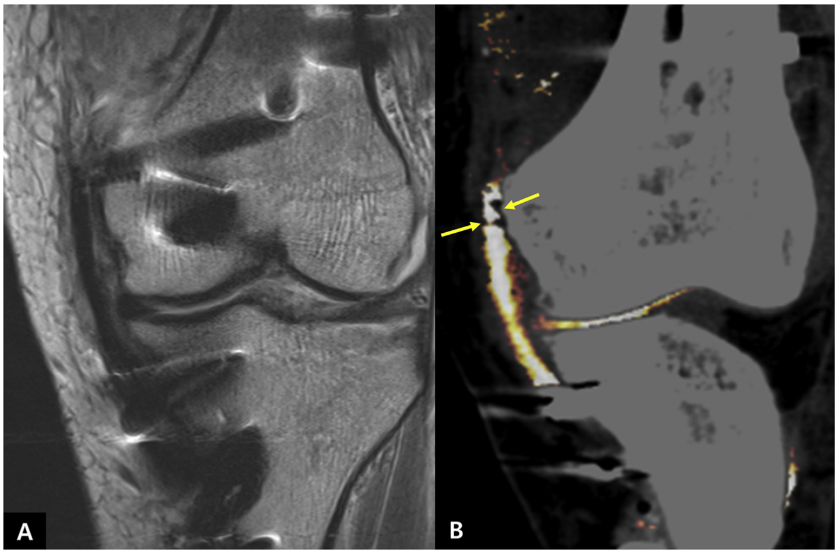

Fig. 6. A 40-year-old male who underwent left medial collateral ligament (MCL) reconstruction using tibialis anterior allograft. Dual-energy CT (DECT) was performed at 8 weeks after surgery and follow-up MRI was performed 2 weeks after DECT. The MCL graft was clinically intact confirmed by physical examination, including negative valgus stress test. (A) Coronal T2-weighted (TR/TE, 4960/63) MRI of the left knee showed the intact MCL graft. (B) Coronal DECT tendon-specific color image demonstrated full 'dual-energy color staining' in the MCL graft (score 2). Partial 'color staining loss' of the proximal MCL graft (arrow) was affected by metal artifact around the femoral fixation screw.

Table 1
Total visualization scores of reconstructed knee ligaments.

	Total visualization score	*p*-value
ACL (n = 30)	4.3 ± 1.7	0.19
Allograft (n = 16)	4.7 ± 1.6	
Autograft (n = 14)	3.9 ± 1.8	
PCL (n = 20)	5.0 ± 0.8	0.94
Allograft (n = 14)	5.0 ± 1.1	
Autograft (n = 6)	5.0 ± 0.6	
MCL (n = 12)	5.4 ± 0.7	0.37
Allograft (n = 2)	5.0 ± 0.0	
Autograft (n = 10)	5.5 ± 0.7	
LCL (n = 10)	5.5 ± 0.5	1.0
Allograft (n = 5)	5.5 ± 0.6	
Autograft (n = 5)	5.5 ± 0.7	
PLC (n = 7)	5.4 ± 1.0	0.85
Allograft (n = 4)	5.3 ± 1.0	
Autograft (n = 2)	6.0 ± 0.0	
ALL (n = 6)	5.3 ± 0.6	0.95
Allograft (n = 3)	5.3 ± 0.3	
Autograft (n = 3)	5.4 ± 1.4	
MPFL (n = 7)	5.8 ± 0.5	0.9
Allograft (n = 4)	5.8 ± 1.6	
Autograft (n = 3)	5.7 ± 0.5	

Note.—Data are the mean ± standard deviation.

Table 2
Frequencies of visualization scores for reconstructed knee ligaments.

Ligament	Frequency of visualization score (%)		
	0	1	2
ACL	15.7 (14/90)	24.5 (22/90)	59.8 (54/90)
PCL	4.7 (3/60)	23.8 (14/60)	71.5 (43/60)
MCL	0 (0/36)	16.7 (6/36)	83.3 (30/36)
LCL	0 (0/30)	16.7 (5/30)	83.3 (25/30)
PLC	4.7 (1/21)	9.5 (2/21)	85.8 (18/21)
ALL	0 (0/18)	22.2 (4/18)	77.8 (14/18)
MPFL	0 (0/21)	8.3 (2/21)	91.7 (19/21))

Note.—Numbers in parentheses are raw data. Percentages were rounded.

could often not be clearly visualized on DECT tendon-specific color image, even if intact continuity.

Compared with MRI, DECT benefits from ultrafast examination time, lower cost, and is less susceptible patient motion. Particularly in patients with knee ligament reconstruction, DECT has advantages in assessing postoperative tibial and femoral bone tunnels or metallic fixation devices [18–20]. At our institution, when the patient is scheduled to take a second-look arthroscopy for hardware removal after the integration of the graft, MRI is used as a preoperative imaging protocol for evaluating graft continuity. Given the results of current study, if no sign of ligament instability or postsurgical complication is identified, DECT could be a possible alternative to MRI in the routine preoperative workup for removal of hardware. DECT collagen material decomposition technique could help reduce the need for MRI examination after knee ligament reconstruction, and patients who have a contraindication to MRI or an economic burden of high cost of MRI could potentially benefit from the DECT. Although there are concerns of radiation dose associated with DECT imaging, judicious use of DECT techniques holds the potential of drastically reducing radiation exposure, for example, by the use of tin filter in dual-source DECT system [21–23]. Low-dose technique, although not addressed here, could enhance the advantages of DECT such as rapid acquisition time, low cost and widespread availability.

Our study has some limitations. First, our study has only included the normal tendon grafts, like some kind of a preliminary study, and not addressed the torn or failed grafts in knee ligament reconstruction. Because the small sample size of ruptured grafts during the observation period of this study (i.e. eight (7.7%) out of 103 patients), it was difficult to evaluate the diagnostic value of DECT for detection of postoperative ligament injury. However, given the results of this study, as more than 95% of the intact ligament grafts, except ACL, were displayed full or partial 'dual-energy color staining', prominent decrease or loss of 'dual-energy color staining' within the graft might be assumed to be related to the graft tear. Further study would be warranted to estimate the performance of DECT in assessing graft tears after knee ligament surgery. Second, not all reconstructed tendon grafts' integrity were confirmed by second-look arthroscopy. However, the facts that the operated knee was clinically normal and the follow-up MRI taken after DECT demonstrated intact continuity would compensate the arthroscopic findings. Third, the range of time of the DECT in relation to the date of surgery might have influenced the results. As the edema could obscure the reconstructed ligament in the acute setting, we excluded DECT performed at the early postoperative period and tried to ensure a time interval more than 6 weeks between surgery and postoperative DECT. However, it could not fully preclude the possibility that some remaining edema in the subacute setting might have affected the visual analysis of DECT. Forth, operative techniques as to specific graft type (e.g. hamstring, Achilles, tibialis anterior, or quadriceps tendon) and graft preparation (e.g. two-strand, three-strand, four-strand or more graft configuration) were not assessed, since it was beyond our scope to compare the effect of different surgical techniques on DECT collagen decomposition algorithm. Fifth, since the number of cases per ligament group was rather small (e.g. PLC, ALL, and MPFL) and there was a 5-fold difference in the number of cases between the largest and smallest groups, these may limit the generalizability of our results. Thus, further studies with a larger population could strengthen the current findings.

In conclusion, DECT collagen material decomposition technique could be a valuable tool to qualitatively display tendon grafts in the patients with knee ligament reconstruction, but more caution would be needed to assess ACL graft.

Conflicts of interest

The authors declare that they have no conflicts of interest

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