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ARTHROSCOPY AND SPORTS MEDICINE

No added value using SPECT/CT to analyze persistent symptoms after anterior cruciate ligament reconstruction

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Abstract

Purpose To evaluate the diagnostic and clinical value of SPECT/CT compared to the standard algorithm for patients with persistent symptoms after anterior cruciate ligament reconstructions. The standard algorithm uses clinical information, conventional radiographs, MRI and CT scan, while the trial algorithm uses the same information but SPECT/CT in addition.

Methods In a diagnostic comparative trial three experienced surgeons evaluated 23 consecutive patients with persistent symptoms after ACL reconstruction using first standard and second the trial algorithm with a time interval. Each rater had to establish a diagnosis and therapeutic decision with each algorithm. On MRI, graft continuity, bone marrow edema, chondral and meniscal lesions, femoral notch osteophytes were evaluated. Bone tracer uptake in SPECT/CT was anatomically analyzed and compared with MRI findings. MRI findings and SPECT/CT tracer uptake were correlated using Spearman's rho test.

Results Additional SPECT/CT analysis did not change diagnosis in any case and did not correlate with clinical graft integrity. Treatment decisions remained unchanged as well. Chondral lesions, arthritic changes, meniscal lesions, graft impingement are best visualized in MRI and showed correspondent tracer uptake in SPECT/CT. Tunnel position was well classified with standard CT scan and showed no correlation with SPECT/CT tracer uptake.

Conclusion Information derived by SPECT/CT in addition to the standard algorithm using clinical information, X-rays, MRI, and CT scan did not change the diagnosis or treatment plan. There is currently no justification to implement SPECT/CT for patients with persistent symptoms after anterior cruciate ligament reconstructions.

Level of evidence Level II: diagnostic comparative study.

Keywords Knee · ACL · Anterior cruciate ligament · SPECT/CT · MRI

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Introduction

According to recent health surveys, approximately 250,000 anterior cruciate ligament reconstructions (ACLR) are performed each year in the US and Europe alone [1]. With this high number of surgical procedures the incidence of patients presenting with problems after ACLR is rising proportionally. The exact incidence of failed ACL procedures is still unknown but data from national registries showed that almost 10% of all ACL procedures are revision surgeries [2]. The most common symptoms are persistent instability and/or pain and can be caused by multiple factors including graft failure or impingement, patient compliance including insufficient rehabilitation or premature return to high-demand activities, or poor operative technique such as tunnel positioning, failure of graft fixation or foreign body reactions [3, 4]. Also concomitant lesions (i.e., meniscal tears or cartilage damage) are often underestimated and may cause accelerated arthritic changes [5]. Therefore, failure of ACL reconstruction can be caused by soft tissue and bony pathologies and require an extended diagnostic algorithm to enable distinguished diagnosis and treatment plan.

In symptomatic ACLR the diagnostic algorithm is crucial to provide the patient with counseling and treatment. In most clinics around the globe the standard noninvasive diagnostics include clinical examination, standardized radiographs, and magnetic resonance imaging (MRI) to determine the success of the treatment or to identify the source of disability. Computerized tomography (CT) has been shown to add valuable information regarding tunnel placement and is frequently added to the assessment if the patient suffers from instability [6]. Furthermore, clinical, functional, and patient-orientated assessments (including hop tests, knee arthrometry, and outcome questionnaires) provide good information as a noninvasive standardized evaluation of the treatment [7, 8]. Lastly diagnostic arthroscopy provides the highest sensitivity and specificity to evaluate intraarticular structures of the knee but includes an invasive procedure and should only be considered with an associated arthroscopic treatment [9]. CT scans have been validated for analysis of the subchondral bone, tunnel size and placement, whereas MRI showed excellent sensitivity for graft and ligament integrity and soft-tissue alterations [8, 10]. To date, MRI with optional combination of CT scan is the preferred advanced imaging modality for the evaluation of symptomatic ACL reconstructions [10, 11].

Recently, the combination of single-emission computed tomography and conventional computer tomography (SPECT/CT) has been proposed in the diagnostic algorithm for patients with a symptomatic knee after ACLR [12]. The modality of SPECT/CT allows combining the metabolic tracer uptake with the accuracy and digital resolution of CT scans to localize the source of the patient's pathology [13]. In particular, several studies have demonstrated a higher sensitivity and specificity for SPECT/CT than for MRI in detecting meniscal tears [14–16]. Therefore, scintigraphy has been considered in addition to MRI, introducing additional information, which is commonly derived from scintigraphy but not available from MRI. Hirschmann et al. developed an algorithm to evaluate and correlate SPECT/CT tracer uptake with graft-bone fixation and graft positioning [12, 17]. The authors found their algorithm to be highly reliable and clinically feasible [12]. Moreover, other authors also found good intra- and interobserver reliability with good applicability of SPECT/CT analysis [18].

However, the same group also reported that the interpretation and correlation of SPECT/CT findings with clinical symptoms seem to be more difficult [19]. On one hand the authors showed that femoral and tibial tunnel misplacement resulted in increased tracer uptake whereas clinical tests for stability or laxity (i.e., Lachman and Pivot shift test) showed no correlation. Also, SPECT/CT found no correlation to graft integrity and joint laxity, the authors concluded SEPCT/CT could be advantageous in the diagnostic algorithm of patients with failed ACLR.

The purpose of this study was to correlate SPECT/CT findings with the gold-standard imaging of symptomatic patients after ACLR and to evaluate the value for a subsequent treatment decision. The hypotheses were as follows: (1) the combined analysis of SPECT/CT and MRI shows a significant divergence of imaging interpretation, compared to CT and MRI alone; (2) the additional information provided from SPECT/CT would lead to different treatment decisions by the raters and (3) SPECT/CT shows a positive correlation with pathological findings on MRI and CT.

Materials and methods

In this diagnostic comparative study we included 23 consecutive patients (11 women and 12 men) with symptoms of knee pain after ACLR. Inclusion criteria were patients with history of a primary ACL reconstruction and complaining about pain and/or instability of their knee, which limited their activities of daily living. Patients with revision ACL's, multiligament injuries and other intraarticular surgery were excluded from the study ($n = 15$). Informed consent was obtained from all individual participants included in the study. The local ethics committee approved the study. The mean age when presenting at our institution was 38.1 (range 19–56), the mean age at the initial ACL reconstruction was 31.8 (range 18–43). Duration of symptoms until patients presented at our clinic ranged from 9 months to 19 years. After clinical assessment further diagnostic analysis with MRI and SPECT/CT was performed within 3 months. The final treatment decision followed thereafter. The following grafts were used in the ACL reconstruction: semitendinosus and/or gracilis tendon ($n = 19$), patellar tendon ($n = 3$), and quadriceps tendon ($n = 1$). For femoral fixation of the graft an interference screw was used in 6 patients, press-fit technique in 3 patients, and endobutton-type fixation in 14 patients. For tibial fixation of the graft, an interference screw was used in 19 patients, and an additional tibial button in four patients. Four patients (17%) reported injury leading to their symptoms after primary ACL reconstruction. Seven patients (30%) complained about chronic instability with giving-way symptoms and locking sensations, 10 patients (43%) reported load-dependent, aching knee pain and 4 patients (17%) reported extension deficit, which limited their daily life. The diagnostic algorithm was performed as follows: three experienced knee surgeons evaluated the clinical files of 23 consecutive patients with persistent symptoms after ACLR using either the above-listed standard or trial algorithm. The evaluation was performed in randomized order and blinded to patient information (raters 1–3). First, MRI datasets were evaluated with CT scans and secondly MRI with SPECT/CT. Sufficient time and randomly changed order were given between the two assessments (Δ 4 months) to avoid recognition. The assessment of the MRI and CT images was performed according to predefined criteria (see radiographic evaluation). CT scan was ordered for evaluation of the femoral and tibial tunnel morphology and orientation. Given the fact that this analysis may become highly variable, the criteria were kept strictly descriptive and qualitative in nature. For this the raters were trained in radiographic analysis of SPECT/CT by a musculoskeletal radiologist, prior to analysis to avoid variability in image interpretation.

Each rater had to establish a diagnosis and treatment plan with each algorithm. Because of the variable treatment options, the recommendations of the raters were merged into three treatment modalities: (1) non-operative treatments such as physical therapy, ultrasound, iontophoresis, insoles, oral medications, or articular infiltration [hyaluronic acid, platelet-enriched plasma (PRP)]; (2) minor surgery (arthroscopy, chondral or meniscal debridement, notchplasty, cyclops removal, microfracturing); or (3) major surgery including revision ACL, meniscus surgery, chondral procedures (autologous chondrocytes implantation/transplantation) or tibial or femoral osteotomies.

Radiographic evaluation

MRI datasets were performed with a 3 or 1.5 T system (Skyra/ Avanto, Siemens, Erlangen, Germany) with a specific knee coil (QED 15 canal, Siemens, Erlangen, Germany). Digital image reconstructions were available in sagittal, coronal, and axial planes with T1- and T2-weighted sequences with a slice thickness of 3 mm.

MRI data were analyzed to evaluate ACL graft integrity, bone bruise, cartilage, and meniscus damage, as well as other soft-tissue alterations such as cyclops or free body formations. The ACL status was classified as intact, completely torn or partially torn when the graft showed enlargement, high signal intensity, focal thinning or a partially wavy course of the graft fibers [20]. Tunnel pathologies were recorded in presence of fluid enhancement or cystic formations. Bone bruises were recorded as increased signal intensity visible on short tau inversion recovery (STIR) or T2-weighted images with a size of $\geq 5 \times 5$ mm. These bruises are a result of increased water content due to trabecular microfractures [21]. Cartilage lesions were classified by location (patella, femoral groove, medial or lateral compartments) and severity (≥ 3 according to the ICRS classification [22]), cartilage thinning (ICRS grade 1 or 2) was not documented. Meniscal damage was noted but type of lesion was not further specified.

Tibial and femoral tunnel morphology and orientation were assessed relative to anatomical knee axis on CT scans. The femoral graft position was measured based on the quadrant method described by Bernard and Hertel [23]. On the roof of the intercondylar notch along the Blumensaat line the posterior and anterior margin of the tunnel was measured and divided by two to determine the center of the graft. This distance relative to the total width of the notch resulted in the graft position. A graft positioned in the posterior 25% was considered as ideal [24]. The femoral graft angle was measured on the coronal slides. The transepicondylar line intersecting with the line from the center of the femoral entry point to the center of the graft in the tibia built the graft angle [25]. Considering the literature femoral angle between 40° and 60° was classified as low (equivalent to the 9–10 o'clock position), 61°–75° as intermediate (i.e., 10–11 o'clock position) and > 75° as high (i.e., high noon position) [26]. The tibial tunnel position was determined in % relative to the total anterior–posterior and medial–lateral length of the tibial plateau with an optimal placement between 41 and 50% [27, 28].

The SPECT/CT analyses were conducted with a Symbia T2 device (Siemens, Erlangen, Germany) with a one-step procedure for bone scintigraphy and CT. Patients received commercially available 740 MBq of 99mTc-DPD and bone scintigraphy was performed 3.5 h after injection with a multiplanar two-dimensional reconstruction in three phases (SPECT: 128 × 128 matrix, 32 frames, 35 s per frame, step and shoot). The following CT scan produced multislice images (130 keV, 70–100 mA) of the knee joint with sagittal, coronal, and axial reconstructions. Slice thickness was 1 mm.

The description of the SPECT/CT data was evaluated according O'Duffy et al. [29] for relative intensity of scintigraphy: Grade 0 showing normal activity in the late bone phase related to the background taken as an area over the distal third of the ipsilateral tibia, grade 1 indicating a target-to-background ratio of between 1 and 2 and Grade 2 a target-to-background ratio of more than 2. Each rater noted the respective maximums on seven localizations: femur (medial, lateral, tunnel), tibia (medial, lateral, tunnel), and patella.

Statistical analysis

Statistical analysis was performed using SPSS software (version 21.0, SPSS Science Inc., Chicago, IL, USA). For analysis of the different imaging modalities a one-way repeated measures ANOVA test was used followed by a Fisher's post hoc analysis. Statistical significance was set at $p < 0.05$. For inter- and intraobserver reliability testing, the internal consistency coefficient (ICC) was calculated using Cronbach's α [30]. The rater's analyses were converted into numbers to allow statistical computation of the three raters and their respective treatment recommendation. The results were merged and graded as follows: > 0.8 very good, 0.8 < α > 0.7 good; 0.7 < α > 0.5 acceptable, < 0.5 poor consistency. Spearman's rho test was used for correlation of SPECT/CT tracer uptake with MRI ($p \leq 0.05$). A two-sided 95% confidence interval (CI) was added.

Results

In comparison to MRI/CT the diagnosis and proposed treatment modalities did not differ from SPECT/CT analysis. The treatment decision-making between non-operative treatments (1), minor surgery (2) and major surgery (3) did not change in any case with additional SPECT/CT data (Table 5). The treatment decisions showed good-to-very good inter- and intraobserver correlations (Cronbach α 0.8 and 0.91, respectively) (Table 2).

The CT-based tunnel analysis showed 13 patients (57%) with a femoral tunnel in the posterior 25% of the femoral epicondyle and 10 (60%) were located between 26–50%. The mean elevation angle of the graft was 70° (SD ± 5.8°). One femoral tunnel (4%) was angulated 45–60°, whereas 17 tunnels (74%) were located between 61–75°. Five tunnels (22%) showed higher angles than 75°. The mean tibial graft position was 45% (SD ± 7.3%) in the anterior–posterior direction measured from the anterior edge of the tibial plateau and 46% (SD ± 2.2%) in the medio-lateral direction measured from the medial edge of the tibial plateau. Five tunnels (22%) were located anterior below 40%, 15 (65%) were positioned between 41–50% and three (13%) posteriorly at more then 50% (Table 1).

MRI analyses revealed an intact graft in 18 patients (78%), two grafts (13%) were enlarged in diameter but with intact continuous fibers and five grafts (22%) were considered torn. In 10 patients (43%) notch impingement was diagnosed. In 17 patients (73%) a meniscus tear was documented (14 medial, 3 lateral lesions). 4° grade chondral lesions were detected on the femoral condyles in 9 patients (39%), on the tibial surface on 4 patients (17%) and on the patella in 7 patients (30%) (Table 1).

We found high inter- and intraobserver correlation for cartilage (0.85, 0.8, respectively), meniscus (0.8 and 0.78, respectively), and graft continuity (0.9 and 0.87, respectively) in MRI (Table 2).

A significant positive correlation between MRI and SPECT/CT analysis was found between femoral and tibial tunnel pathology (i.e., tunnel enlargement, fluid enhancement), with bone tracer uptake in the femoral and tibial tunnel on SPECT/CT (Fig. 1). Moreover, tracer uptake on the medial femoral condyle and tibial plateau positively correlated with fourth-degree chondral lesions on the femur and tibia seen in MRI. Also, bone bruises diagnosed on MRI showed correspondent tracer uptake on the medial and lateral tibial plateau on SPECT/CT (Table 3). Graft continuity did not correlate with bone tracer uptake.

Femoral graft position showed a positive correlation with tracer uptake in the femur. A more anterior-positioned tibial tunnel correlated with more tracer uptake in the femoral and tibial tunnel and medial tibial plateau (Table 4).

Table 1 CT and MRI evaluation of ACL tunnel and soft tissue (*n* = number of patients, with total of 23)

ACL tunnel analysis (CT based)		Soft-tissue measurements (MRI based)	
Variable	*n* (%)	Variable	*n* (%)
Femoral tunnel		Graft integrity (α 0.91)	α
< 25% (posterior)	13 (57)	Intact	18 (78)
26–50% (intermediate)	10 (43)	Torn	5 (22)
51–75% (anterior)	0	Notch impingement	10 (43)
Femoral angle		Cartilage lesion	
45°–60°	1 (4)	Femur	9 (39)
61°–75°	17 (74)	Tibia	4 (17)
> 75°	5 (22)	Patella	7 (30)
Tibial graft position (a.-p.)		Meniscus tear	
Anterior < 40%	5 (22)	Medial	14 (60)
Central (41–50%)	15 (65)	Lateral	3 (13)
Posterior (> 50%)	3 (13)		
Tibial graft position (m.-l.)		Subchondral bone bruise	
Medial (< 40%)	0	Femoral	4 (17)
Correct (41–50%)	23 (100)	Tibial	6 (26)
Lateral (> 50%)	0		
Tunnel enlargement femoral		Tunnel enlargement tibial	
None	9 (39)	None	16 (70)
Moderate	12 (52)	Moderate	6 (26)
Advanced	2 (9)	Advanced	1 (4)

Tunnel enlargement (tibia and femur): no = up to 10 mm; moderate = 11–14 mm, advanced > 15 mm; tibial position anterior–posterior: anterior = 0–40%, correct 41–50%, posterior > 50%; tibial position medio-lateral: medial 0–40%, correct 41–50%, lateral > 50%; femoral graft angle: low = 45°–60°, intermediate = 61°–75°, high > 75°; femoral graft position: posterior < 25% (correct), intermediate 26–50%, anterior > 50%

ACL anterior cruciate ligament, *MRI* magnetic resonance imaging

Discussion

SPECT–CT was introduced as a new diagnostic tool in the algorithm of failed ACLR. Thus we studied the standard and trial algorithms and compared for additional clinical value. The most important findings of the present study are as follows: the additional information derived from SPECT/CT did not change the treatment decision in any case compared

Table 2 Cronbach's α intraobserver reliability and intraobserver agreement according to diagnostic evaluation

Observer criteria	MRI/CT	SPECT/CT	Treatment decision	
			MRI/CT	MRI + SPECT/CT
Interrater correlation				
Mean	0.8	0.82	0.8	0.8
Level of agreement	Very good	Very good	Very good	Very good
Intrarater correlation				
Mean	0.85	0.91	0.91	0.9
Level of agreement	Very good	Very good	Very good	Very good

Treatment decisions between MRI/CT and SPECT–CT were not significantly different ($p < 0.05$)

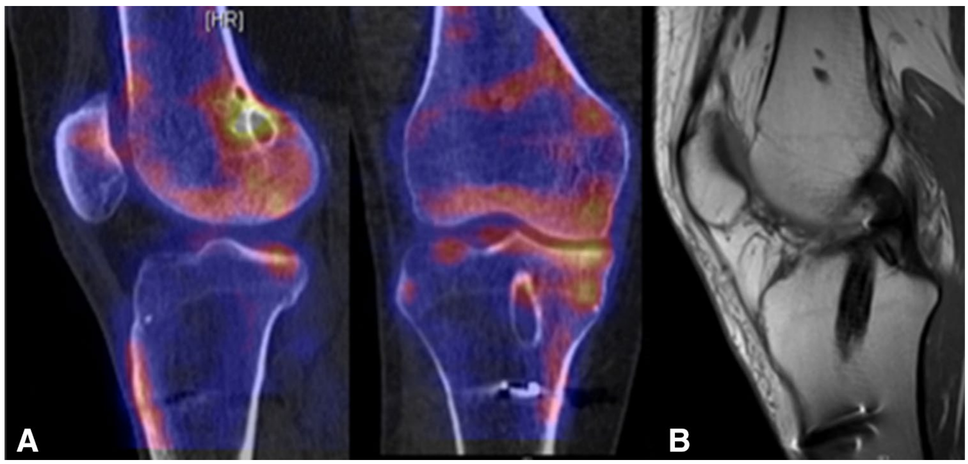

Fig. 1 SPECT /CT image with tracer uptake at the femoral canal and the medial joint space correlating with a high femoral angle and posterior tibial canal measured in CT scan (**a**) and progressive osteoarthritis and cartilage degradation measured in MRI (**b**)

to MRI/CT alone. However, findings such as tunnel enlargement, cyst formations, meniscal tears, fourth-degree cartilage lesions of the femur and tibia, and bone bruises diagnosed through MRI significantly correlated with bone trace uptake in SPECT/CT. Thus, SPECT/CT may replace MRI in certain clinical circumstances, but the additional information has no added value in the standard algorithm using MRI and CT scan only.

There are certain limitations, which have to be considered when interpreting our results. This investigation presents a diagnostic comparative study. Therefore, this study remains a diagnostic approach to illuminate treatment decision-making. To investigate and demonstrate the superiority of one or the other radiological technique we would need a prospective randomized clinical trial with exactly defined treatment criteria, based on the standard or trial algorithm. Instead, this study aimed to mimic, as closely as possible, the daily clinical decision-making based on diagnostic and clinical information. Moreover, it is important to mention the heterogeneity of this cohort. The 23 subjects did undergo ACLR using a variety of different surgical techniques, grafts, and fixation techniques. It is possible that the differences could have masked small specific SPECT/CT patterns, which did not reach significance. However, none of the patients had a treatment shift because of the additional information of the SPECT/CT. Lastly, we merged treatment recommendations into three categories (i.e., non-operative, minor and major surgery). This fact might have masked subtle differences between the recommendations of the raters. However, the recommendations were very homogenous with only a few deviations between the inter- and intraobserver correlation (Table 5).

Interestingly, the additional information obtained with SPECT/CT did not show any impact regarding the treatment decision. In all 23 patients the treatment decision remained the same even with the additional information from the SPECT/CT analysis. This result disproves both of our hypotheses: Firstly, we did not find a significant divergence of imaging interpretation between MRI and SPECT/CT. On the contrary, SPECT/CT and MRI showed very good correlation. Secondly, SPECT/CT did not alter the therapeutic treatment plan compared to MRI and CT alone.

In the analysis of the pathologies of this cohort we either found soft-tissue problems, such as graft integrity, meniscal tears and notch impingement (cyclops), or bone bruise and chondral defects. These pathologies are accurately diagnosed with MRI. The remaining diagnoses consisted of tunnel pathologies (misplacement, enlargement). They incorporate the most prevalent cause of failure in ACL-R

Table 3 Correlation of SPECT/CT tracer uptake and MRI analysis

SPECT/CT	MRI										
	Graft	Tunnel pathology		Notch	4° cartilage defect			Bone bruise		Meniscal tear	
	continuity	Tibia	Femur	Impingement	Patella	Femur	Tibia	Femur	Tibia	Medial	Lateral
Femur											
Medial	0.2 (−0.2; −0.5)	0.1 (−0.3; 0.5)	−0.2 (−0.5; 0.1)	−0.2 (−0.4; 0.3)	0 (−0.3; 0.4)	**0.5*** **(0; 0.8)**	**0.6*** (0.3; 0.8)	0.3 (0; 0.2)	0.3 (−0.2; 0.4)	−0.1 (−0.6; 0.1)	0 (−0.2; −0)
Lateral	−0.3 (−0.5; −0.1)	0.1 (−0.4; 0.3)	0.2 (−0.2; 0.6)	0.2 (−0.1; 0.6)	0 (−0.3; 0.4)	0.1 (−0.3; 0.5)	0 (−0.3; 0.4)	0.3 (0; 0.2)	0.2 (−0.3; 0.5)	−0.1 (−0.5; 0.3)	−0.2 (−0.4; −0.1)
Tunnel	−0.2 (−0.5; 0.2)	**−0.4*** **(−0.6; −0.2)**	**−0.4*** **(−0.3; 0.3)**	**0.5*** **(0.2; 0.8)**	0.2 (−0.4; 0.5)	−0.1 (−0.5; 0.2)	0.1 (−0.4; 0.3)	−0.1 (0; 0.2)	−0.3 (−0.5; −0.1)	−0.3 (−0.5; 0.3)	−0.1 (−0.4; 0.3)
Tibia											
Medial	−0.1 (−0.4; 0.3)	**0.5*** **(0.2; 0.6)**	−0.1 (−0.4; 0.3)	0 (−0.4; 0.4)	−0.4 (−0.7; 0.1)	0.1 (−0.4; 0.5)	**0.4*** **(0.1; 0.6)**	0 (0.3; 0.3)	**0.5*** **(0; 0.8)**	−0.1 (−0.5; 0.3)	0.1 (−0.3; 0.5)
Lateral	−0.2 (−0.4; −0.1)	0 (−0.3; 0.5)	−0.1 (−0.2; 0.1)	0.3 (−0.1; 0.5)	0 (−0.3; 0.3)	0.1 (−0.3; 0.5)	−0.2 (−0.3; −0.1)	**0.5*** **(0.2; 0.8)**	**0.4*** **(−0.2; 0.6)**	0.1 (-0.3; 0.4)	-0.2 (-0.3; 0.1)
Tunnel	0 (−0.5; 0.5)	−0.3 (−0.7; 0.1)	0.2 (−0.1; 0.5)	0.1 (−0.2; 0.5)	**0.4*** **(−0.3; 0.7)**	0 (−0.4; 0.4)	0.1 (−0.4; 0.6)	0 (−0.4; 0.4)	−0.3 (−0.1−0.6)	−0.1 (−0.5; 0.2)	0.1 (−0.2; 0.4)
Patella	0 (−0.2; 0.5)	0.2 (−0.2; 0.6)	0.3 (−0.1; 0.7)	0.1 (−0.3; 0.4)	0.2 (−0.2; 0.6)	0.1 (−0.3; 0.5)	0.1 (−0.2; 0.6)	−0.2 (−0.3; −0.1)	0 (−0.3; 0.4)	−0.2 (−0.5; 0.1)	−0.2 (−0.3; −0.1)

Significant correlations are in bold. Values above 0.75 are considered as excellent correlation, 0.40–0.75 as fair-to-good and below 0.40 as poor. 95% confidence interval (95% CI) with upper and lower bond

*$p < 0.05$

Table 4 Correlation of SPECT/CT tracer uptake and MRI/CT scan analysis

SPECT/CT	MRI/CT					
	Tibia			Femur		
	Enlargement	Position ap	Position ml	Enlargement	Angle	Position
Femur						
Medial	−0.1 (−0.4;0.3)	0.1(−0.3;0.5)	0 (−0.4;0.4)	−0.1 (−0.4;0.4)	−0.3 (−0.5;0.1)	**0.46*** **(0.2;0.6)**
Lateral	−0.3 (−0.6;0)	0.1 (−0.2;0.5)	0.2 (0;0.4)	0.2 (−0.2;0.6)	0.1 (−0.3;0.6)	−0.1 (−0.4;0.3)
Tunnel	−0.22 (−0.5;−0.1)	**−0.1 (−0.4;0.4)**	0 (−0.2;0.3)	0.1 (−0.2;0.5)	−0.1 (−0.5;0.3)	−0.1 (−0.5;0.3)
Tibia						
Medial	0.2 (−0.1;0.5)	**0.5*** **(0.2;0.6)**	0.3 (−0.1;0.5)	−0.1 (−0.4;0.3)	0.1 (−0.3;0.4)	−0.2 (−0.5;0.2)
Lateral	−0.3 (−0.6;0.1)	0.1 (−0.2;0.5)	−0.12	0.2 (−0.2;0.6)	0.3 (−0.2;0.8)	0.1 (−0.3;0.5)
Tunnel	0 (−0.4;0.3)	**−0.1 (−0.6;0.4)**	0.16	−0.3 (−0.6;0.2)	−0.2 (−0.5;0.3)	−0.1 (−0.6;0.4)
Patella	0.1 (−0.4;0.7)	0.1 (−0.3;0.5)	0.34	−0.1 (−0.3;0.3)	−0.2 (−0.4;0.1)	−0.1 (−0.4;0.2)

Significant correlations are in bold. 95% confidence interval (95% CI) with upper and lower bond

*$p < 0.05$

due to instability and can be accurately diagnosed with CT scan [31].

The additional information provided by SPECT/CT highlights the tracer uptake towards osteoblastic activity. This may be upregulated by mechanical or anatomical malalignment leading to mechanical stress in the underlying subchondral compartment. In our cohort we found a positive correlation between tunnel misplacement, chondral degradation and bone marrow edema with bone tracer uptake indicating a biological stress. However, we could not demonstrate a clinical consequence of the additional data from the SPECT/CT regarding the treatment decision because all pathologies have been sufficiently visualized by the standard algorithm using MRI and CT scan. Thus, the high financial costs and additional radiation exposure can only be justified if when MRI analysis is not suitable because of the presence of pacemaker, foreign metal bodies in orbits or vascular clips. Due to high financial costs and additional radiation exposure the treating physician should carefully evaluate if SPECT/CT would be beneficial to the treatment of the patient.

Recently, Hirschmann et al. introduced a diagnostic algorithm, correlating SPECT/CT with MRI and clinical findings in patients with ACL-R. They found their algorithm to be easily applicable with high inter- and intraobserver reliability [12]. They found significant correlation comparing the tunnel position and orientation after ACL reconstruction. A more recent study from the same group also showed a positive correlation of synovial thickening seen in MRI with local bone tracer uptake found in SPECT/CT [32]. However, the clinical instability measured by pivot shift, anterior drawer or Lachman test could not be correlated with the graft orientation or 99mTC-HDP-SPECT/CT tracer uptake [19]. The same group investigated the correlation of MRI and SPECT/CT in patients complaining about knee pain after ACLR. They found similar results as in our investigation with increased bone tracer uptake in the femur and tibia and bone marrow edema. They also found a positive correlation with graft integrity with more bone tracer uptake in more complete ACL tears [33]. The authors concluded that SPECT/CT can be a valuable diagnostic tool providing additional valuable information. However, positive signals should not be rated as graft failures in general, because uptake did not correlate with graft failure. Thus, positive uptake may be a physiologic sign of intact graft which takes load and thus causes physiological increased tracer uptake.

Although we found similar results for excellent correlation between SPECT/CT and MRI findings, SPECT/CT findings are usually indirect visualizations of pathologic bone turn over and thus matter of clinical interpretation. On MRI the pathologies can be visualized directly without the need for interpretation. Thus, whenever possible, the MRI should be favoured over SPECT/CT in symptomatic knees after ACLR.

Conclusion

Information derived by SPECT/CT additional to the gold standard of MRI did not change the diagnosis or treatment plan. There is no diagnostic or clinical value to implement SPECT/CT to the standard algorithm for patients with persistent symptoms after ACLR.

Table 5 Treatment decision shift according to diagnostic modalities (MRI + CT vs. MRI + SPECT/CT)

Patient	MRI + CT				MRI + SPECT/CT				Treatment shift
	Proposed treatment			Treatment class	Proposed treatment			Treatment class	
	Rater 1	Rater 2	Rater 3		Rater 1	Rater 2	Rater 3		
1	M, N, C	M, C	M, N, C	2	M, N, C	M, C	M, N, C	2	No
2	ACL-R	ACL-R	ACL-R	3	ACL-R	ACL-R	ACL-R	3	No
3	ACL-R	ACL-R	ACL-R	3	ACL-R	ACL-R	ACL-R	3	No
4	P	P	P	1	P	P	P	1	No
5	P	P, M	P	1	P	P, M	P	1	No
6	UK	UK	UK	3	UK	UK	UK	3	No
7	N, AL, M, HTO	N, AL, M	N, M, HTO	3 (2)	N, AL, M, HTO	N, AL, M	N, M, HTO	3 (2)	No
8	M	M	M, AL	2	M, N	M	M, AL, TR	2	No
9	ACL-R, M	ACL-R, M	ACL-R, M	3	ACL-R, M	ACL-R, M	ACL-R, M	3	No
10	M	M, N	M	2	M, N	M, N	M	2	No
11	N, C, M	N, C, M	N, M	2	N, C, M	N, C, M	N, M	2	No
12	ACL-R, TR	ACL-R, M, TR	ACL-R, TR	3	ACL-R, TR	ACL-R, M, TR	ACL-R, TR	3	No
13	P	P	P	1	P	P	P	1	No
14	ACL-R, M, ACT	ACL-R, M	ACL-R, M, ACT	3	ACL-R, M, ACT	ACL-R, M	ACL-R, M, ACT	3	No
15	TKA	TKA	TKA	3	TKA	TKA	TKA	3	No
16	ACL-R, N, HTO, ACT	ACL-R, N, HTO, ACT	ACL-R, N, HTO, ACT	3	ACL-R, TR, ACT, HTO	ACL-R, N, HTO, ACT	ACL-R, N, HTO, ACT	3	No
17	N, TR	N, TR, (ACLR)	N, M, TR	3	N, TR	N, TR	N, M, TR	3	No
18	N, AL	N, AL	N, AL	2	N, AL	N, AL	N, AL	2	No
19	N, ACT, AL	AL, ACT, M	N, ACT, AL	3	N, ACT, AL	AL, ACT, M	N, ACT, AL	3	No
20	N, M	N, M	N, M	2	N	N, M	N, M	2	No
21	ACL-R, N, TR	ACL-R, N	ACL-R, N, TR	3	ACL-R, N, TR	ACL-R, N	ACL-R, N, TR	3	No
22	ACL-R, M	ACL-R, M	ACL-R, M	3	ACL-R, M	ACL-R, M	ACL-R, M	3	No
23	N, C	N, C	N, C, M	2	N, C	N, C, M	N, C, M	2	No

(1) Non-operative: physiotherapy (P) (i.e., exercise, ultrasound, iontophoresis etc.), insoles, oral medications, articular infiltration (hyaluronic acid, platelet-enriched plasma, autologous-conditioned plasma)

(2) Minor surgery: arthroscopic procedure (A): meniscal revision (M), cyclops (C) or osteophyte (O) removal, chondral debridement, femoral notchplasty (N), arthroscopic arthrolysis (AL)

(3) Major surgery: revision ACL reconstruction (ACL-R), tunnel revision (TR), chondral reconstruction (AMIC; ACI, OATS), arthroplasty (TKA, UK), realignment surgery (HTO)

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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