Knee Surg Sports Traumatol Arthrosc (2014) 22:3039–3046
DOI 10.1007/s00167-013-2698-2

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Assessment of in vivo loading history of the patellofemoral joint: a study combining patellar position, tilt, alignment and bone SPECT/CT

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Received: 30 December 2012 / Accepted: 27 September 2013 / Published online: 11 October 2013

Abstract
Purpose The current study investigates whether patella height and tilt or leg alignment influence the intensity values as well as the distribution pattern of single photon emission computerized tomography/computerized tomography (SPECT/CT) tracer uptake in the patellofemoral joint.
Methods 99mTc-HDP-SPECT/CT and radiographs of consecutive 84 knees were prospectively obtained. Lateral radiographs were analyzed in terms of patellar height, Insall-Salvati index and modified Insall-Salvati index. Skyline views were analyzed for Laurin's lateral patellofemoral angle. On long-leg radiographs, the mechanical leg alignment was classified as varus, valgus or neutral. SPECT/CT was analyzed for each anatomical region using a previously validated SPECT/CT localization and grading algorithm. Mean, standard deviation, minimum and maximum of grading for each area of the localization scheme were recorded. Non-parametric Spearman's correlations were used to correlate patellar height, lateral patellar angle and leg alignment with the tracer uptake intensity. Chi-square statistics were used for categorical data ($p < 0.05$).
Results A patella baja correlated significantly with higher SPECT/CT tracer uptake in all patellar and lateral femoral regions ($p < 0.001$). A higher lateral patellar tilt correlated significantly with higher tracer uptake in the superior lateral femoral parts and the tibial tubercle. In mechanically varus aligned knees, there was significantly higher SPECT/CT tracer uptake on the medial and in valgus knees on the lateral part of the patellofemoral joint ($p < 0.05$).
Conclusions As the intensity and distribution of the SPECT/CT significantly correlated with patella baja and patellar tilt, SPECT/CT might be considered as imaging modality for evaluating patients with patellofemoral disorders and for follow-up of patients after patellofemoral realignment procedures.
Level of evidence Diagnostic study, Level II.

Keywords Knee · SPECT/CT · Patella · Loading · Tilt · Patella height

Introduction

Realignment procedures such as tibial tubercle medialization and anteriorization aim to reduce the mechanical loading on the patellofemoral joint [1, 24]. Others such as trochleoplasty strive to improve the stability of the patellofemoral joint without increasing the patellofemoral contact pressure [3, 6]. In in vitro studies, a patella infera position has been related with altered contact areas and increased pressure within the patellofemoral joint [26, 31, 34].

To date, there is no optimal imaging modality, which could be equally sensitive and specific to identify changes in patellofemoral joint loading. Recently, the benefits of single photon emission computerized tomography/computerized tomography (SPECT/CT) have been highlighted

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in orthopaedic patients with knee problems [10–17, 19, 32]. SPECT/CT is a hybrid imaging, which combines 3D scintigraphy (SPECT) and CT into one imaging modality. The most commonly used tracers are diphosphonates, which target active osteoblasts. SPECT/CT offers the benefits of combined anatomical, mechanical (CT) and functional (SPECT) imaging [10–15, 19]. In a previous study, Hirschmann et al. [18] found that the intensity and distribution of SPECT/CT tracer uptake within the tibiofemoral joint reflect the loading pattern of the knee joint with regard to the mechanical and anatomical alignment.

SPECT and SPECT/CT are able to give valuable information about in vivo joint loading of the tibiofemoral joint [18, 25]. Biomechanically the patellofemoral joint is not only exposed to the joint reaction and loading forces but also shear forces. Hence, it was unclear whether SPECT/CT is also a useful imaging modality for the evaluation of in vivo joint loading of the patellofemoral joint. In this case, it could be established as novel imaging modality evaluating patients with patellofemoral disorders and for follow-up of patients after patellofemoral realignment procedures.

The purpose of this study was to investigate whether the position of the patella as well as the mechanical alignment influences the intensity and the distribution pattern of bone SPECT/CT tracer uptake in the patellofemoral joint. The hypotheses were that an increased 99mTc-HDP tracer uptake in SPECT/CT images would be present within the patellofemoral compartment in situations of altered patella position such as patella infera, patella alta, overly tilted patella or in varus or valgus malalignment of the femorotibial joint (Fig. 1).

Materials and methods

99mTc-HDP-SPECT/CT and conventional radiographs of consecutive 84 knees ($n = 71$ patients, male:female = 33:38, mean age 48 ± 16) were prospectively obtained. The patients underwent these imaging modalities due to knee pain. Exclusion criteria were a known history of avascular necrosis of the knee, a tumour, Paget's disease, joint infection, periarticular fracture, neuropathic arthropathy, reactive arthritis, gout, arthroscopic surgery within the last 3 months.

Skyline views as well as lateral radiographs were obtained. Lateral radiographs were then analyzed in terms of patellar height, the Insall-Salvati index (normal range

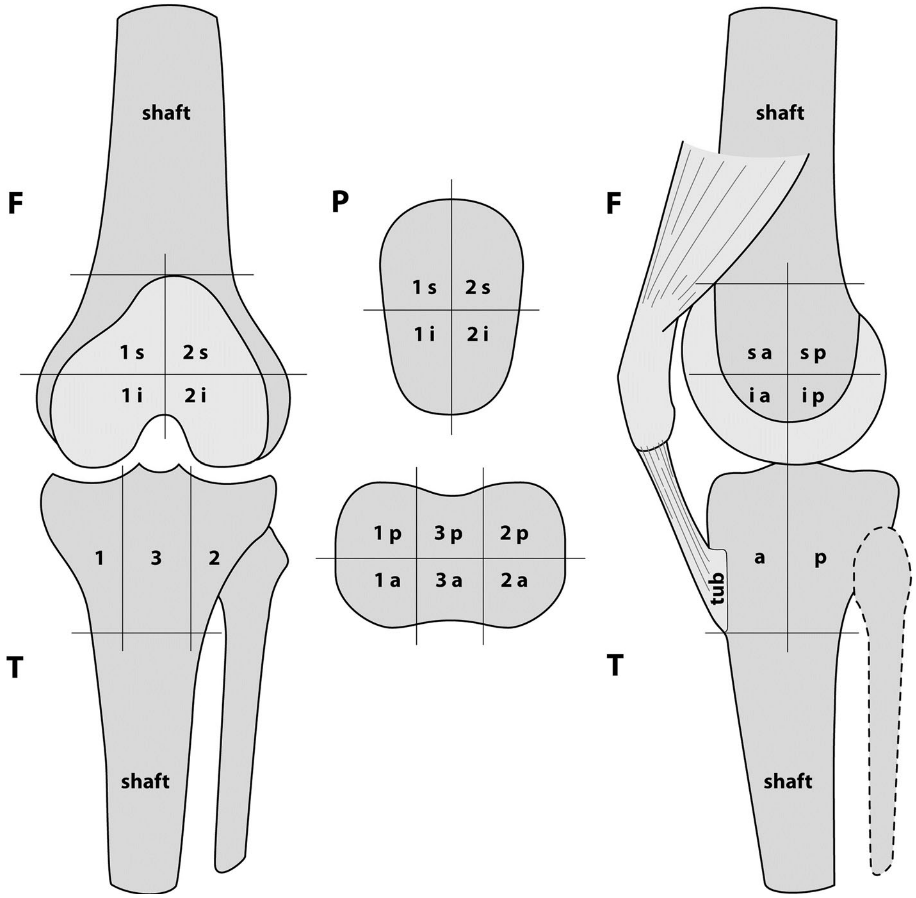

Fig. 1 The localization scheme, which allows grading and identification of increased SPECT/CT tracer uptake in each patellofemoral area of interest

0.8–1.2) and the modified Insall-Salvati index (normal range <2) [9, 20]. The Caton-Deschamps index was also measured on lateral radiographs [5]. Skyline views were analyzed measuring the lateral patellofemoral angle according to Laurin [28] (Fig. 2).

Long-leg radiographs (femur to ankle) were obtained in standing position with the tibial tubercle facing forward. The X-ray beam was centred at the knee at a distance of 2.4 m. A setting of 100–300 mA/s and 80–90 kV was used. These radiographs were used to assess the mechanical leg alignment, which was then classified as varus, valgus or neutral. Mechanical alignment was measured as the angle at the intersection of a line connecting femoral head and intercondylar notch centre with a line connecting talar surface centre and tibial eminence sulcus base. Knee alignment of 180° ± 1 from the full-limb radiograph was taken as neutral axis. Angles of less than 179° were labelled varus, and angles greater than 181° were labelled valgus alignment. In addition, three different patellar tilt angles were measured on CT slices (Fig. 3).

The patellar tilt angle according to Grelsamer was measured as the angle between the mid-patellar line and the horizontal line [8]. The patellar tilt angle according to Sasaki [33] was measured as the angle between the mid-patellar line and the anterior trochlear line. The patellar tilt angle modified by Fulkerson [7] was measured as the angle between the mid-patellar line and the posterior condyle line. The angle was indicated as positive when it was open medially.

The tibial tuberosity trochlear groove (TT-TG) distance was measured. It was indicated as positive when the tibial tuberosity was lateral in relation to the trochlear groove.

All SPECT/CTs were performed using a Symbia T16 (Siemens, Erlangen, Germany). The CT collimation was 16 × 0.75 mm. Planar scintigraphic images were taken in three phases, the perfusion phase (immediately after injection), the soft tissue phase (1–5 min after injection) and the delayed metabolic phase (2–3 h after injection). A commercial 700 MBq Tc-99m-HDP tracer (Mallinckrodt, Wollerau, Switzerland) was used. Delayed SPECT images were obtained with a matrix size of 128 × 128, an angle step of 32, and a time per frame of 25 s 2–3 h after injection.

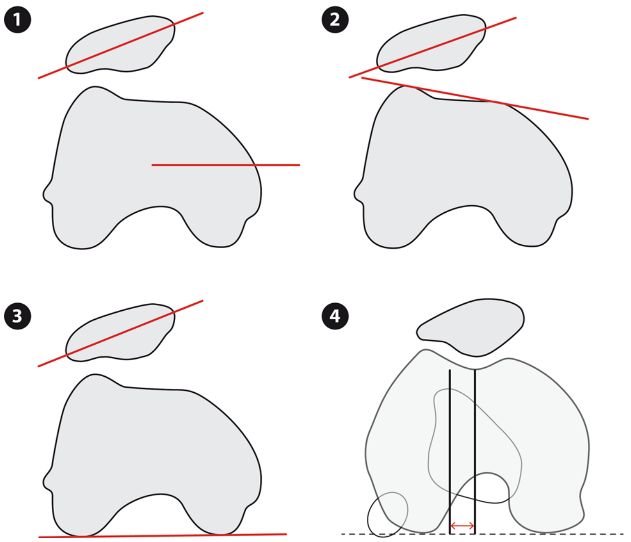

Fig. 3 Schematically transaxial CT slices of a distal right femur (1–3) and a transaxial slice in overlay technique of a distal right femur and a proximal. This figure shows three methods of measuring the patella tilt angle described by Grelsamer (1), Sasaki (2) and Fulkerson (3). Nr. 4 illustrates the measurement of the TT-TG distance in overlay technique. [7, 8, 33]

Data were processed by interactive reconstruction and images were displayed in transaxial, coronal and sagittal planes (Syngo, Siemens, Erlangen, Germany).

The SPECT/CT images were analyzed for the patellofemoral regions using a previously validated SPECT/CT localization and grading algorithm (Fig. 1) [18]. The localization and grading scheme, which showed high inter- and intra-observer reliability, defines 8 tibial, 9 femoral and 4 patellar regions. The anatomical area (femur, tibia, patella) is indicated with capital letters (F, T, P). The femur (F) is divided into nine zones which include one shaft and eight distal femoral zones. Each

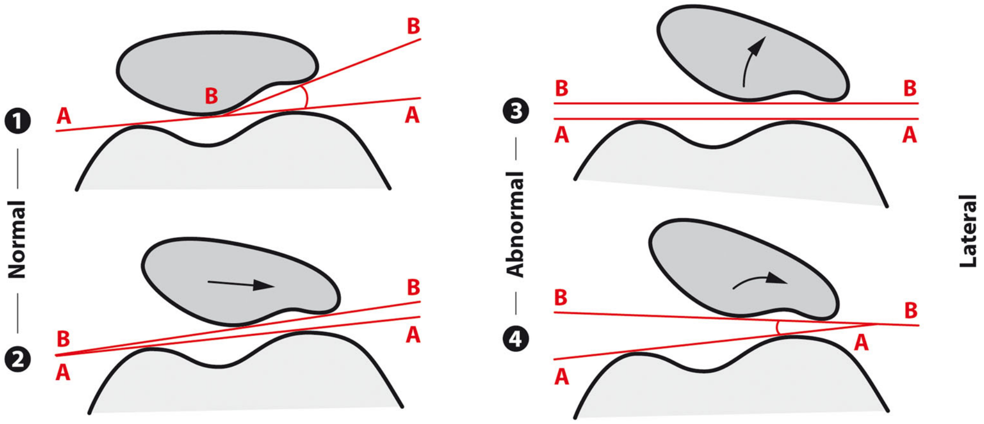

Fig. 2 The upper part of the figure shows the measurement of the lateral patellofemoral angle according to Laurin. The lateral patellofemoral angle is formed by the lines A–A and B–B. Normally, the angle is open laterally. In knees with an abnormal lateral angle, the lines are parallel or the angle is open medially. [28]

distal femoral zone is represented with a number (1 for medial, 2 for lateral) and two small letters (a-anterior, p-posterior and s-superior, i-inferior). The tibia (T) is divided into eight zones which include one shaft region, one region of the tibial tubercle and six tibial regions. Each tibial zone is represented with a number (1 for medial, 2 for lateral, 3 for mid zone) and a small letter (a-anterior, p-posterior). The patella (P) is divided into four zones (superomedial, superolateral, inferomedial and inferolateral).

Mean, standard deviation, minimum and maximum of grading for each area of the localization scheme were recorded using a semiquantitative colour-coded grading scale (0–10). The inter-observer reliability and intra-observer reliability quantified by intraclass correlation coefficients (ICC) were all >0.85. The inter-observer agreement and intra-observer agreement for measurements on radiographs were described previously by Specogna et al. [35]. The study was approved by the local ethical committee of Basel (EKBB EK 91/10) (Fig. 4).

Statistical analysis

Data were analyzed using SPSS 17.0 (SPSS, Chicago, USA). Nonparametric Spearman's correlation coefficients were used to correlate the patella height, the lateral patellar angle and leg alignment measurements with the intensity of tracer uptake in each area of interest. The values of the patella height and the lateral patellar angle measurements were also correlated categorically using chi-square statistics. The normal range for each index was set as normal, the values below and above the normal range as other categories. The level of statistical significance was defined as $p < 0.05$.

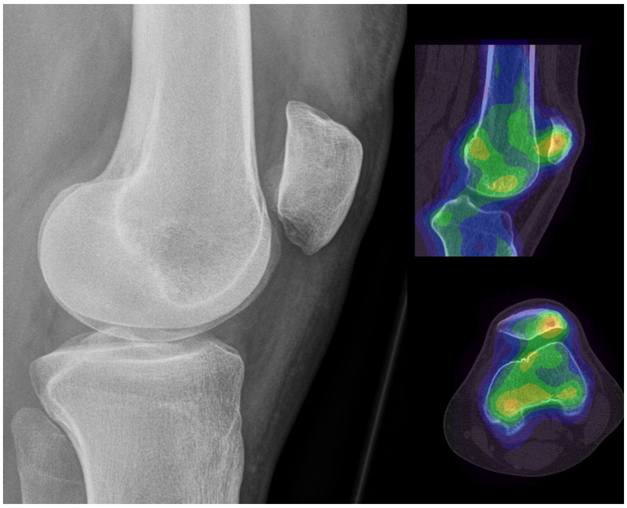

Fig. 4 Lateral radiograph (*left*) and 99m-Tc-SPECT/CT (*right*) of a 25-year-old patient's left knee. In this case, the Insall-Salvati index (1.15) was within the normal range (0.8–1.2). The SPECT/CT showed increased tracer uptake in the lateral patellar facet

Results

Patella height measurements were available of 84 knees and categorized in Table 1. Lateral patellar angle measurements according to Laurin were mean 5.54 ± 3.18°. On long-leg radiographs, 16 (19 %) knees showed valgus, 34 (40.5 %) varus and 34 (40.5 %) neutral mechanical alignment. The mean patellar tilt angle according to Grelsamer was 7 ± 9°, the mean patellar tilt angle according to Sasaki was 15 ± 7° and the mean patellar tilt angle modified by Fulkerson was 8 ± 7°. The mean tibial tuberosity trochlear groove distance was 9 ± 11 mm.

A lower patella position correlated significantly with higher 99mTc-HDP-SPECT/CT tracer uptake in all patellar and lateral femoral regions ($p < 0.001$). A higher lateral patellar angle in radiographs correlated significantly with higher 99mTc-HDP tracer uptake in the superior femoral parts such as F1s, F1sa, F1sp, F2sp and the tibial tubercle. In CT, a higher patellofemoral tilt angle according to Sasaki and Fulkerson correlated significantly with increased tracer uptake in the lateral superior zones (F2s $p < 0.01$, F2sa $p < 0.01$) and the lateral superior and inferior patella (P2s, P2i). An increased TT-TG was significantly correlated with decreased tracer uptake in the tibial tuberosity and the lateral superior patellar zone (P2s $p < 0.05$).

Univariate Spearman's correlations between 99mTc-SPECT/CT tracer uptake in each patellofemoral region of interest and analysis of patella position are presented in Table 2.

The intensity of 99mTc-HDP-SPECT/CT tracer uptake on the medial part of the patellofemoral joint significantly correlated with mechanical varus alignment of the knee ($p < 0.05$). The intensity of 99mTc-HDP tracer uptake on the lateral part of the patellofemoral joint significantly correlated with mechanical valgus alignment of the knee ($p < 0.05$) (Table 3).

Discussion

This present study investigated whether patellar tilt, patellar height or mechanical alignment influence the intensity and the distribution pattern of SPECT/CT tracer uptake in the patellofemoral joint. The most important findings of this study were threefold:

Firstly, a lower patella position significantly correlated with higher 99mTc-HDP-SPECT/CT tracer uptake within the patellofemoral compartment of the knee. Interestingly, a patella alta condition did not lead to an increase in

Table 1 The patellar height documented using the Insall-Salvati index and the modified Insall-Salvati index categorized into three classes (−1 = below the neutral range, 0 = within the neutral range, 1 = above neutral range)

	Insall-Salvati (neutral 0.8–1.2)		Modified Insall-Salvati (neutral <2)		Caton-Deschamps (neutral 0.6–1.2)	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
−1	9	11.3	–	–	1	1.3
0	61	76.3	77	96.3	70	87.5
1	10	12.5	3	3.8	9	11.3
Total	80	100	80	100	80	100

Table 2 Univariate Spearman's correlations of 99mTc-SPECT/CT tracer uptake in each patellofemoral region of interest and patella measurements (* = $p < 0.05$, ** = $p < 0.01$)

	Insall-Salvati >1.0	Insall-Salvati <1.0	Modified Insall-Salvati	Caton-Deschamps	Caton-Deschamps >0.9	Caton-Deschamps <0.9	Lateral patellar angle °
F1s	−0.05	0.19	−0.10	−0.07	−0.07	0.05	0.41**
F1i	−0.09	0.09	0.03	−0.09	−0.12	−0.01	−0.13
F2s	0.01	0.29**	−0.28*	−0.15	−0.12	0.17	0.22
F2i	−0.03	0.36**	−0.21	−0.12	−0.12	0.12	0.09
F1sa	−0.04	0.21	−0.09	0	−0.01	−0.02	0.37*
F1ia	−0.08	0.18	−0.05	−0.02	−0.06	−0.05	−0.01
F1sp	−0.07	0.15	−0.04	−0.14	−0.15	0.07	0.36*
F1ip	−0.15	0.05	0.05	−0.19	−0.23*	0	−0.11
F2sa	−0.02	0.21	−0.21	−0.03	−0.08	−0.04	0.21
F2ia	−0.01	0.24*	−0.17	−0.09	−0.13	0.03	−0.03
F2sp	−0.04	0.28*	−0.09	−0.14	−0.09	0.2	0.33*
F2ip	−0.02	0.29**	−0.03	−0.18	−0.15	0.21	0.24
F	−0.08	0.3**	−0.15	−0.12	−0.14	0.07	0.27
T Tub	−0.02	0.27*	0.02	−0.1	−0.09	0.08	0.35*
P1s	−0.10	0.26*	−0.18	−0.05	−0.13	−0.06	0.05
P1i	−0.08	0.31**	−0.23*	−0.07	−0.11	0	0.18
P2s	−0.11	0.23*	−0.19	−0.06	−0.13	−0.05	0.01
P2i	−0.1	0.25*	−0.27*	−0.04	−0.09	−0.04	0.17
P	−0.11	0.27*	−0.24*	−0.06	−0.13	−0.04	0.11

SPECT/CT tracer uptake within the patellofemoral joint. To date, there has not been any study showing a relationship between patellofemoral alignment and SPECT or SPECT/CT tracer uptake. Only other imaging modalities such as MRI and conventional radiographs were used to assess this relationship [21–23, 34].

Our findings are at least partially in contrast with others showing correlations between osteoarthritic changes and a patella alta [36]. Singerman et al. [34] investigated in an in vitro study the effects of patella alta and infera position on patellofemoral contact forces. They found that in a patella alta position, the magnitude of the patellofemoral contact continued to increase with increasing flexion angle [34]. A patella infera position resulted in a decrease in the patellofemoral contact force [34]. The medially directed component of the contact force acting on the patella increased with superior displacement of the patella [34]. The resultant contact force migrated superiorly with inferior displacement of the patella [34].

It has been shown by Kalichman [21–23] that for MRI patellar alignment measurements such as Insall-Salvati ratio, sulcus angle and lateral patellar angle are related to cartilage loss and bone marrow oedema. A patella alta position was significantly associated with increasing cartilage loss in both medial and lateral compartments of the patellofemoral joint and with bone marrow oedema in the lateral compartment [21–23].

Secondly, a higher lateral patellar angle in radiographs and CT correlated significantly with higher 99mTc-HDP tracer uptake in the superior lateral femoral zones, the

Table 3 Univariate Spearman's correlations between 99mTc-SPECT/CT tracer uptake in each patellofemoral region of interest and the upper and lower half of leg alignment measurements

	Mechanical alignment >4	Mechanical alignment <4
F1 s	0.02	−0.12
F1i	−0.18	0.16
F2 s	0.14	−0.27*
F2i	0.25*	−0.29**
F1sa	0.08	−0.17
F1ia	−0.11	0.08
F1sp	0.06	−0.12
F1ip	−0.11	0.15
F2sa	0.10	−0.22*
F2ia	0.21	−0.28**
F2sp	0.16	−0.28**
F2ip	0.25*	−0.26*
F	0.08	−0.17
T Tub	0.07	−0.17
P1s	0.17	−0.20
P1i	0.25*	−0.27*
P2s	0.14	−0.17
P2i	0.21	−0.24*
P	0.21	−0.22*

Increased valgus when alignment >4°, increased varus when alignment <4°. (* = $p < 0.05$, ** = $p < 0.01$)

lateral superior and inferior patella zones and the tibial tubercle. An increased TT-TG was significantly correlated with decreased tracer uptake in the tibial tuberosity and the lateral superior patellar zone.

Physiologically it is understood that in normally aligned knees with normally shaped patellofemoral joints, the loading is bigger on the lateral than on the medial facet. This is due to the physiological valgization of the femorotibial joint [2].

Kalichman reported that increased sulcus angle and lateral patellar tilt angle were related to increased cartilage loss and bone marrow oedema [22, 23]. Numerous studies investigated the relationship of bone marrow oedema in MRI and patellofemoral osteoarthritis or pain level [22, 23]. The question whether areas of present bone marrow oedema in MRI represent areas of increased SPECT/CT tracer uptake has not sufficiently been answered. However, Buck et al. [4] reported findings that all patients with bone marrow oedema in MRI showed abnormal bone scintigraphy and vice versa. Approximately one out of ten patients showed no bone marrow oedema but tracer uptake in bone scintigraphy. It seems that bone marrow oedema does not represent the identical pathophysiology. Interestingly, Lo et al. [29] found that the bone mineral density correlated with the occurrence of bone marrow lesions in MRI.

Thirdly, mechanical alignment significantly influenced 99mTc-HDP tracer uptake of the patellofemoral compartment of the knee. Patients with more mechanical valgus alignment had significantly increased values of the SPECT/CT tracer uptake for the medial patellofemoral region. Patients with more varus mechanical alignment had significantly decreased values of the SPECT/CT tracer uptake of the medial and lateral patellar regions.

In case of patellofemoral pain, chronic instability or localized patellofemoral osteoarthritis realignment procedures such as tibial tubercle anteriorization or medialization are part of the surgeon's armamentarium [1, 24, 27]. These aim to unload areas of cartilage lesions and overloading [1, 24, 27]. One problem before and after these procedures is that one does not want to increase the load in these regions [37].

Importantly to date, there is no optimal imaging modality, which is able to visualize areas of increased loading and stress. Lorberboym et al. [30] pointed out that SPECT was 100 % sensitive and 64 % specific in detecting patellofemoral lesions when compared with arthroscopy. SPECT/CT has been increasingly recognized as promising imaging modality not only for patients with patellofemoral problems [10–15].

The knowledge established in the present study about the influence of mechanical as well as patellofemoral alignment on SPECT/CT tracer uptake distribution is of paramount importance. SPECT/CT could be used as an adjunct imaging modality in patients before and after patellofemoral surgery. In the daily clinical work, SPECT/CT could then help to determine which knee compartment is overloaded and subsequent treatment can be minimized to the affected compartment.

A number of limitations have to be considered. In our study, rotational alignment of the femur or tibia was not assessed, but could significantly influence the distribution of SPECT/CT tracer uptake. In addition, there might be a difference in SPECT/CT tracer uptake in symptomatic and asymptomatic patients. The influence of the degree of osteoarthritis present has been investigated in a previous study. Here it was shown that it is correlated, but not the decisive factor.

Conclusion

SPECT/CT reflects the in vivo loading within the patellofemoral joint. The intensity and distribution of the SPECT/CT significantly correlated with patella infera and patellar tilt, measured in conventional radiographs. Based on these findings, SPECT/CT is promising for evaluating patients with patellofemoral disorders and for follow-up of patients after patellofemoral realignment procedures.

Acknowledgments We greatly thank the Deutsche Arthrose-Hilfe e.V., Frankfurt am Main, Germany, the Gottfried und Julia Bangerter-Rhyner-Stiftung, Berne, Switzerland for their support to our research.

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