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Clinical Utility of Continuous Radial Magnetic Resonance Imaging Acquisition at 3 T in Real-time Patellofemoral Kinematic Assessment: A Feasibility Study

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Abstract

Purpose—To compare patellar instability with magnetic resonance imaging analysis using continuous real-time radial gradient-echo (GRE) imaging in the assessment of symptomatic patients and asymptomatic subjects.

Methods—Symptomatic patients with suspected patellofemoral maltracking and asymptomatic volunteers were scanned in real time by a radial 2-dimensional GRE sequence at 3 T in axial orientation at the patella level through a range of flexion-extension. The degree of lateral maltracking, as well as the associated tibial tubercle–trochlear groove distance and trochlea depth, was measured. Patellar lateralization was categorized as normal (≤ 2 mm), mild (>2 to ≤ 5 mm), moderate (>5 to ≤ 10 mm), or severe (>10 mm). The patellofemoral cartilage was also assessed according to the modified Outerbridge grading system.

Results—The study included 20 symptomatic patients (13 women and 7 men; mean age, 36 ± 12.8 years) and 10 asymptomatic subjects (3 women and 7 men; mean age, 33.1 years). The

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mean time to perform the dynamic component ranged from 3 to 7 minutes. Lateralization in the symptomatic group was normal in 10 patients, mild in 1, moderate in 8, and severe in 1. There was no lateral tracking greater than 3 mm in the volunteer group. Lateral maltracking was significantly higher in symptomatic patients than in asymptomatic subjects (4.4 ± 3.7 mm vs 1.5 ± 0.71 mm, $P = .007$). Lateral tracking significantly correlated with tibial tubercle–trochlear groove distance ($r = 0.48$, $P = .006$). There was excellent agreement on lateral tracking between the 2 reviewers (intraclass correlation coefficient, 0.979; 95% confidence interval, 0.956–0.990).

Conclusions—The inclusion of a dynamic radial 2-dimensional GRE sequence is a rapid and easily performed addition to the standard magnetic resonance imaging protocol and allows dynamic quantitative assessment of patellar instability and lateral maltracking in symptomatic patients. With a paucity of reported data using this technique confirming that these results reach clinical significance, future work is required to determine how much lateral tracking is clinically significant.

Level of Evidence—Level III, case control.

Accurate measurement of patellar tracking is important in the diagnosis and treatment of patellofemoral disorders. The method of muscle loading, range, direction of knee motion, use of static or dynamic measurement techniques, and tibial rotation all affect the results obtained.^{1,2} As a result, there are numerous limitations and shortcomings of the conventional methods of patellofemoral kinematic evaluation. Furthermore, the accuracy of the method used is important because differences in tracking may be small.^{1,2} The utility of magnetic resonance imaging (MRI) is well established in the assessment of patellofemoral maltracking. It has been proposed that by using a combination of static and dynamic techniques, patients can be classified more accurately than with the use of static studies alone.^{3–6} Although previous work has described dynamic sequences for patellofemoral maltracking, the required high temporal resolution and the need for mechanisms to control flexion and extension, as well as the requirement for post processing, have made performing these scans impractical in day-to-day practice.^{7–10}

With the development of fast MRI sequences, true dynamic studies have become feasible without a requirement for special post processing.¹¹ Techniques such as real-time ultrafast MRI using a combination of a fast low-angle shot (FLASH) or true fast imaging with steady-state precession (FISP) sequence with radial data sampling and view sharing of successive acquisitions allow for high-speed and motion-robust examinations.^{12–17} This allows for a temporal resolution of up to 50 milliseconds per frame and low-latency online display of the images without the need for offline processing on external hardware. It has shown utility in imaging movements of the temporomandibular joint during voluntary opening and closing of the mouth at high spatial resolution (0.75-mm in-plane resolution),¹⁸ monitoring cardiac function,^{19,20} imaging the gastrointestinal tract,²¹ and performing dynamic perfusion.²² However, these fast MRI techniques have not yet been evaluated in a clinical setting for the peripheral skeleton.

The purpose of this study was to compare patellar instability with MRI analysis using continuous real-time radial gradient-echo (GRE) imaging in the assessment of symptomatic patients and asymptomatic subjects. Our hypothesis was that this added sequence could

differentiate symptomatic patients with patellar instability on clinical examination from asymptomatic subjects without symptoms or positive findings on clinical examination.

Methods

This study was approved by the institutional review board. All patients gave informed consent.

Participants

Between December 2015 and December 2016, patients were identified directly by orthopaedic surgeons (D.K., M.A., K.C., L.J.) on the basis of clinical examination findings or by a musculoskeletal radiologist (C.B.) from the radiology MRI electronic work list (Primordial, San Mateo, CA) with the specific clinical indication for MRI assessment of patellofemoral instability or maltracking. The inclusion criteria were patients with positive signs of patellar instability on physical examination and age 18 years or older. The signs included increased passive patellar translation (translation of the medial pole of the patella 2 quadrants laterally), positive J-sign (lateral translation of the patella in extension with reduction of the patella in early flexion as it engaged with the trochlea), and patellar apprehension test (guarding of the patella with passive lateral translation).²³ Patients who could not comfortably flex their knee and those with a history of surgery or with diagnoses other than patellofemoral maltracking were excluded from the study. In the case of bilateral knees, it was arbitrarily decided that patients' right knees would be used. Volunteers were chosen from our institution across a similar age range and were required to be asymptomatic with no history of surgery and no evidence of clinical instability or other diagnoses at the time of the scan. The number of volunteers chosen was based on those available meeting the inclusion criteria at the time of the study.

MRI Technique

All patients were scanned on a standard clinical MRI system with a field strength of 3 T (Magnetom Skyra or Prisma; Siemens Healthineers, Erlangen, Germany). Patients were initially scanned according to a standard protocol using a 15-channel transmit-receive coil. The coil was then exchanged with an 18-channel receive-only body coil with the knee supported for the dynamic imaging component, and patients were asked to slowly flex and extend during the real-time acquisition (Fig 1A).

The sequence used for dynamic imaging followed the design and implementation details described by Zhang et al.,¹⁷ which is available from the system vendor as a works-in-progress package (WIP 610; Siemens). It uses a slice-selective (2-dimensional [2D]) GRE acquisition scheme with radial k-space sampling. We used the refocused variant of the sequence that returns the magnetization to the k-space center at the end of the repetition time, which results in T2- or T1-dependent contrast and which was found to be superior for patellofemoral assessment in comparison with the spoiled GRE version of the sequence. Radial views were continuously sampled with a constant angular distance and 5× interleaved acquisition order, that is, the sequence used 5 rotations for acquiring the views whereas each rotation used a different angular offset so that the views acquired during the individual 5

rotations could be combined into a full k-space dataset. This enabled performing a view-shared reconstruction, in which the views from only 1 rotation were updated for each image frame, resulting in a 5× higher image update rate compared with a full k-space acquisition. Moreover, the sequence used an integrated real-time control mechanism, which allowed adjustment of the slice position interactively during the acquisition and proved helpful for identifying the plane of interest and for correcting the slice position if needed. Images were reconstructed online with a standard gridding algorithm for non-Cartesian data.

An 8-mm-thick axial slice at the level of the patella was scanned continuously over a period of 2 minutes at a temporal resolution of 49 milliseconds per frame through a range of flexion and extension (0°-30°), showing the relation between the patella and the trochlear groove as the patient actively extended from 30° of knee flexion to full extension (Fig 1B). A flip angle of 8° was used for the refocused acquisition scheme, which was chosen experimentally to improve contrast. Other sequence parameters included the following: field of view, 256 mm; base resolution, 128 pixels; repetition time, 2.43 milliseconds; echo time, 1.21 milliseconds; and readout bandwidth, 1,700 Hz/pixel.

Clinical MRI Analysis

Maltracking was characterized as mild (>2 to 5 mm), moderate (>5 to 10 mm), or severe (>10 mm). Normal was categorized as (< 2 mm) (Figs 2 and 3; Videos 1 and 2, available at www.arthroscopyjournal.org).

The tibial tubercle–trochlear groove (TT-TG) distance, sulcus groove depth, Insall-Salvati ratio, and modified Outerbridge patella and trochlea cartilage scores were assessed based on the static sequences using the standard knee coil as has been previously described.²⁴⁻²⁶ The degree of dynamic lateralization was measured using a technique similar to that used by McNally et al.,⁶ in addition to static measurements of patellofemoral morphology, whereby the maximal lateral excursion of the patella margin from neutral was calculated on the dynamic acquisition in the axial plane (Figs 2 and 3). All measurements were made by a musculoskeletal radiologist (C.B.) with 8 years of experience. To examine inter-rater agreement, a second reader (G.C.), with 8 years of musculoskeletal radiology experience, also assessed lateral tracking independently. The MRI analysis was performed using IntelliSpace PACS (Philips, Amsterdam, Netherlands).

Statistical Evaluation

Descriptive statistics, linear regression analysis, and a Mann-Whitney *U* test were performed using SPSS software (version 24; IBM, Armonk, NY). Spearman correlation (*r*) and the *P* value for the association of lateral tracking measured by each reader and the average over readers with the Insall-Salvati ratio, modified Outerbridge patella and trochlea scores, sulcus depth, and TT-TG distance were calculated. Results were calculated for each subject group and for the sample as a whole. Partial correlations that adjusted for a binary indicator of group membership were computed.

Results

The study included 20 symptomatic subjects (13 women and 7 men; mean age, 36 years) with positive signs of patellar maltracking on clinical examination (positive J-sign, patellar translation, and/or patellar apprehension test) and 10 asymptomatic subjects (3 women and 7 men; mean age, 33.1 years). Two symptomatic patients had bilateral symptoms, and both patients' right knees were used (total of 20 symptomatic knees). Descriptive statistics are presented in Table 1. Spearman correlation (r) and the P value for the association of lateral tracking measured by each reader and the average as well as the static measurements are presented in Table 2.

The time to perform the dynamic component ranged from 3 to 7 minutes. Lateralization in the symptomatic group was normal in 10 patients, mild in 1, moderate in 8, and severe in 1. There was no lateral tracking greater than 3 mm in the volunteer group. Lateral maltracking was significantly higher in symptomatic patients than in asymptomatic volunteers (4.4 ± 3.7 mm vs 1.5 ± 0.71 mm, $P = .007$). Lateral tracking significantly correlated with TT-TG distance ($r = 0.48$, $P = .006$). It did not correlate with sulcus depth, Insall-Salvati ratio, or Outerbridge patella or trochlea score (Table 2) on the basis of the primary reader's findings. Although the primary reader did not find sulcus depth to significantly correlate with lateral tracking in the combined, symptomatic, or asymptomatic group ($P = .24$, $P = .07$, and $P = .14$, respectively), the secondary reader did find a significant correlation in the symptomatic group ($P = .043$). Three patients without maltracking showed findings of proximal patellar tendinosis and partial tearing. There was excellent agreement on lateral tracking between the 2 reviewers (intraclass correlation coefficient, 0.979; 95% confidence interval, 0.956-0.990).

Discussion

The results showed that continuous radial 2D GRE imaging allows dynamic quantitative assessment of patellar instability that can discriminate between symptomatic and asymptomatic subjects. Furthermore, the study results showed excellent agreement between the 2 reviewers, and the lateral maltracking measured significantly correlated with TT-TG distance.

Real-time Radial MRI

Numerous authors have described the clinical importance of imaging in the assessment of patellofemoral kinematics because it provides a possible cause of instability. Although computed tomography (CT) has considerable utility for assessing patellofemoral kinematics,²⁷⁻³² the lack of ionization radiation makes magnetic resonance an attractive modality.^{3-6,33}

Previous work has been limited by the speed of the available magnetic resonance techniques limiting utility in routine clinical practice. Static MRI has been used by multiple investigators to obtain axial images at several degrees of flexion that, when viewed in a cine loop, may show subluxation. McNally et al.⁶ developed a dynamic technique that allows patellar tracking to be assessed in the supine position. This technique included active extension while deflating a ball to ensure that the quadriceps contracted throughout the examination. The examination used 15 true fast imaging with steady-state precession (FISP)

sequences on a 1-T scanner, which each took 2 minutes and required post processing. In total, full static and dynamic examination of both knees took up to 60 minutes, making it impractical for routine assessment.⁶

With the advent of sub-second fast imaging, true dynamic studies have become feasible. Draper et al.¹¹ obtained axial-plane kinematic MRI in volunteers with patellofemoral pain by use of a single-slice spiral real-time sequence performing knee flexion-extension in a 0.5-T open MRI scanner with a 5-inch surface coil taped to the knee. Each image was acquired in 171 milliseconds (6 images per second). Continuous image reconstruction was performed using a sliding window algorithm resulting in a reconstructed frame rate of 35 frames per second.

Real-time radial GRE imaging is a simple and versatile tool that can be performed on standard 3-T MRI systems using radial k-space acquisition with view-sharing reconstruction to achieve temporal resolution of up to 50 milliseconds per frame and high-robustness motion artifacts. In addition, it provides near-zero latency image reconstruction directly on the hardware integrated in the MRI scanner. To date, the technique has been used in a range of applications from imaging the temporomandibular joint¹⁸ to monitoring cardiac function during free breathing,¹⁵ and it lends itself well to the dynamic assessment of patellar tracking. The time to complete the additional component of our examination ranged from 3 to 7 minutes, suggesting the technique could be seamlessly integrated into a typical knee imaging protocol.

Patellofemoral Kinematics

Unlike malalignment, which can be appreciated with static views, maltracking is a dynamic phenomenon, which occurs as the knee is flexed. Thus the actual pathology cannot be captured with still images alone, and only malalignment can be appreciated, which is currently used as a surrogate.³² Furthermore, it has been shown that the TT-TG distance may change with leg position as the tibia rotates internally and externally with extension and flexion, making static imaging at a set flexion angle less useful.³⁴ Although the TT-TG distance has been correlated with symptoms, this can be highly variable. Whereas a distance greater than 15 mm on CT may be considered positive, patients with larger distances may be fairly asymptomatic and those with smaller distances may be symptomatic.^{35,36} This amounts to a clear need for improved, or at least supplementary, imaging techniques to better characterize the pathology and guide treatment management. Furthermore, values determined by CT and MRI are frequently not identical.²⁴ The accuracy of CT in TT-TG calculation is well established, and although a correlation has been shown using MRI, values may vary particularly with respect to the knee position and MRI coil used.³⁶

We aimed to show the relation between the patella and the trochlear groove at degrees of flexion less than 30°, at which subluxation is believed to be most prevalent. We applied a patellar lateralization grading system similar to that used by McNally et al.⁶ By use of the same criteria, this sequence showed abnormal lateral patellar tracking in 10 of 20 symptomatic knees, 1 of which was classified as severe. The statistically greater lateral tracking in the symptomatic patients suggests validity of this measuring technique.

Further evidence of legitimacy is achieved through the significant correlation of lateral tracking measured on dynamic MRI with TT-TG distance (the current marker used for instability). This finding suggests that dynamic lateral tracking has the potential to be used as a valid measurement of patellar instability and may be able to augment current imaging examinations to ultimately provide a more accurate and reliable marker of instability. Up to 3 mm of subluxation was detected in volunteers who were without symptoms at the time of the examination, suggesting that mild lateral subluxation may not be clinically significant in isolation. It is recognized that comparative data using this technology are lacking in the literature confirming that these results reach clinical significance and that future studies will be required to quantify the degree of clinically significant lateral maltracking.

Limitations

As with previous work, 1 weakness encountered in this study was the lack of a gold standard for patellar maltracking. A prospective power calculation was not performed to confirm the adequacy of the sample size. The reproducibility and consistency of the kinematic results among repetitive motions were not assessed. There is variation between men and women with respect to patellofemoral kinematics, and the sex ratio varied between the symptomatic and asymptomatic groups. Although the analytical results showed excellent inter-reader reliability, assessment of intra-reader reliability was not performed. The method of patient selection both by the orthopaedic surgeon directly and by the musculoskeletal radiologist from the MRI clinical indication may potentially introduce selection bias. Furthermore, longitudinal follow-up was not available to determine the natural history of subluxation in the mild, moderate, and severe groups. Follow-up studies will report on the outcomes of these different groups.

Conclusions

The inclusion of a dynamic radial 2D GRE sequence is a rapid and easily performed addition to the standard MRI protocol for kinematic patellofemoral motion and allows dynamic quantitative assessment of patellar instability and lateral maltracking in symptomatic patients. With a paucity of reported data using this technique confirming that these results reach significance, future work is required to determine how much lateral tracking is clinically significant.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig 1.

(A) Body coil in situ for dynamic examination. The body coil is strapped in place with the knee held in flexion by a pillow and support to ensure stability. The patient is instructed to extend from 30° of knee flexion to full extension. (B) Magnetic resonance workstation showing multiplanar alignment of the knee during real-time image acquisition with an 8-mm-thick axial slice selected at the level of the patella.

Fig 2.

(A-I) Sequential images from the continuous dynamic gradient-echo sequence in a 26-year-old asymptomatic male volunteer. The acquisition was performed in real time with the patella centered within the axial plane (Video 1, available at www.arthroscopyjournal.org). There was no significant abnormal lateral excursion of the patella margin between 0° and 30° of flexion, measuring 1 mm.

Fig 3.

(A-I) A 27-year-old male patient with anterior knee pain, chondromalacia (grade 2 patella and grade 3 trochlea scores according to modified Outerbridge system), and patellofemoral maltracking on clinical examination. Sequential images are shown from the continuous dynamic gradient-echo sequence obtained in the axial plane, showing the calculation of maximal lateral excursion of the patella margin between 0° and 30° of flexion, measuring 8 mm in this case (Video 2, available at www.arthroscopyjournal.org).

Table 1

TT-TG Distance, Sulcus Depth, Lateral Tracking, Insall-Salvati Ratio, and Outerbridge Patella and Trochlea Grading in Both Symptomatic Patients and Asymptomatic Subjects

Side	TT-TG Distance, mm	Sulcus Depth, mm	Lateral Tracking, mm	Insall-Salvati	Outerbridge Patella Score	Outerbridge Trochlea Score
Symptomatic						
Right	15	8	20	1.3	3	1
Left	19	2	8	1.5	3	1
Left	16	4	6	1.5	4	1
Right	17	7	1	1.1	2	1
Right	25	4	12	1.2	2	1
Left	8	6	1	0.8	1	1
Right	14	4	8	1.3	1	3
Right	9	5	2	1.3	1	2
Left	7	5	0	1.1	1	4
Left	19	2	4	1.3	3	3
Right	12	5	1	1.3	4	4
Left	11	5	0	1.3	3	2
Right	9	6	2	1.5	1	2
Left	19	3	10	1.3	2	3
Right	12	4	1	1	2	2
Left	14	2	2	1.3	2	3
Right	20	3	6	1.6	2	1
Right	20	4	9	1.4	4	4
Left	18	3	7	1.1	3	3
Right	6	3	2	1.1	4	2
Mean $\pm$ SD (95% CI)	14.5 $\pm$ 5.2 (12.1-16.9)	4.25 $\pm$ 1.7 (3.9-5.0)	4.4 $\pm$ 3.7 (2.7-6.1)	1.3 $\pm$ 20 (1.2-1.4)	2.4 $\pm$ 1.1 (1.9-2.9)	2.2 $\pm$ 1.1 (1.7-2.7)
Asymptomatic						
Right	2.5	6	1	1.1	0	0
Right	0	5	1	1.1	0	0
Left	0	6	1	0.9	0	0
Right	1	6	1	1.1	0	0

Side	TT-TG Distance, mm	Sulcus Depth, mm	Lateral Tracking, mm	Insall-Salvati	Outerbridge Patella Score	Outerbridge Trochlea Score
Right	1.5	6	1	0.8	4	4
Right	0	6	1	1.1	0	0
Left	1	4	2	1	0	0
Right	2	5	3	0.9	0	0
Left	0	4	2	1.1	0	0
Right	0	5	2	1	0	0
Mean $\pm$ SD (95% CI)	0.8 $\pm$ 0.95 (0.12-1.5)	5.3 $\pm$ 0.82 (4.7-5.9)	1.5 $\pm$ 0.71 (1.0-2.0)	1.01 $\pm$ 0.11 (0.93-1.1)	0.4 $\pm$ 1.3 (0.51-1.3)	0.4 $\pm$ 1.3 (0.51-1.3)
Total	9.9 $\pm$ 5.3 (7.0-12.8)	4.6 $\pm$ 1.5 (4.0-5.2)	3.43 $\pm$ 3.3 (2.2-4.7)	1.2 $\pm$.21 (1.1-1.3)	1.7 $\pm$ 1.5 (1.8-2.3)	1.6 $\pm$ 1.4 (1.1-2.1)

CI, confidence interval; SD, standard deviation; TT-TG, tibial tubercle–trochlear groove.

Table 2

Spearman Correlation (r) and P Value for Association of Lateral Tracking Measure From Each Reader and Average Over Readers, With Insall-Salvati Ratio, Modified Outerbridge Patella and Trochlea Scores, Sulcus Depth, and TT-TG Distance

Measure	Reader 1		Reader 2		Average	
	r	P	R	P	r (95% CI)	P
All subjects						
Insall-Salvati ratio	0.29	.108	0.2	.293	0.26 (0.11–0.57)	.16
Modified Outerbridge patella score	0.28	.126	0.17	.358	0.22 (–0.15 to 0.54)	.237
Modified Outerbridge trochlea score	0.08	.651	–0.03	.883	0.03 (–0.33 to 0.39)	.873
Sulcus depth	–0.22	.241	–0.37	.042	–0.3 (–0.6 to –0.1)	.099
TT-TG distance	0.48	.006*	0.6	.001*	0.52 (0.20–0.74)	.003*
Symptomatic						
Insall-Salvati ratio	0.32	.145	0.23	.303	0.29 (–0.17 to 0.65)	.186
Modified Outerbridge patella score	0.2	.368	0.26	.236	0.23 (–0.23 to 0.61)	.31
Modified Outerbridge trochlea score	–0.05	.837	–0.03	.888	–0.05 (–0.4 to 0.48)	.841
Sulcus depth	–0.39	.071	–0.45	.038*	–0.44 (–0.74 to 0.00)	.043*
TT-TG distance	0.68	.001*	0.74	<.001*	0.7 (0.37–0.87)	<.001*
Asymptomatic						
Insall-Salvati ratio	–0.15	.67	–0.28	.44	–0.25 (–0.76 to 0.45)	.491
Modified Outerbridge patella score	0.46	.182	0.12	.732	0.31 (–0.40 to 0.79)	.383
Modified Outerbridge trochlea score	0.46	.182	0.12	.732	0.31 (–0.40 to 0.79)	.383
Sulcus depth	0.51	.136	–0.02	.961	0.22 (–0.46 to 0.75)	.538
TT-TG distance	–0.1	.791	0.2	.58	0.06 (–0.59 to 0.66)	.865

NOTE. Results are provided for each subject group and for the sample as a whole. Partial correlations were computed that adjusted for a binary indicator of group membership.

CI, confidence interval; TT-TG, tibial tubercle–trochlear groove.

* Statistically significant.