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ORIGINAL ARTICLE • KNEE - IMAGING

MRI evaluation of the knee with non-ferromagnetic external fixators: cadaveric knee model

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Abstract
Introduction The advent of MRI-compatible external fixation devices has made the use of MRI possible in patients who have been treated with external fixation. However, although there have been multiple studies determining the safety of MRI scans with external fixator devices, there are no studies determining the artifact effect these devices can have on the MRI image. The purpose of our study was to evaluate the effect of two popular brands (Stryker and Synthes) of MRI-compatible external fixators on the diagnostic capacity of a knee MRI. We hypothesize that (1) MRI images would have higher noise due to the presence of an external fixator and (2) images of high diagnostic capacity will be obtainable in the presence of each external fixator spanning the knee.
Methods Using seven cadaveric knees, a study was performed to analyze MRI images taken in the presence each external fixator. Scans taken with no external fixator present served as controls. Signal-to-noise ratios (SNRs) were measured at five anatomic structures. These structures were compared as a quantitative measure of image quality. A qualitative analysis was also performed using a five-point grading scale to assess the influence of metal artifact on the quality of the images. Each scan was graded by three blinded musculoskeletal radiologists focusing on six key anatomic structures.
Results A reduction in SNR was identified on the external fixator group compare to the control groups at the patella tendon, MM and PCL. Qualitative scoring by three expert radiologists showed no difference in ability to identify the six key anatomic landmarks between the Stryker, Synthes and control images.
Conclusion Although the presence of external fixation devices does increase the noise artifact in MRI scans, patients treated with these external fixators can undergo MRI of local structures with high likelihood of obtaining diagnostic quality images.

Keywords Non-ferromagnetic external fixator · Knee · MRI safety · MRI evaluation

Introduction

MRI is a sensitive and reliable imaging technique used to evaluate ligamentous injuries of the knee [1]. Trauma patients with lower extremity fractures and dislocations are at risk of concomitant ligamentous injuries to the ipsilateral knee. External fixation is a commonly used method of initial or definitive stabilization of many lower extremity injuries such as tibial plateau fractures, knee dislocations, open tibia or femur fractures, and floating knee fractures [2]. Certain knee injuries, such as those to the posterior lateral corner, are best treated by early surgical intervention [3]. Therefore, the availability of a reliable MRI scan, in the acute setting, is beneficial for diagnosing such injuries.

Multiple reports in the literature have established the safety of most orthopedic implants in an MRI environment [4–6]. Therefore, MRI has been routinely used as a diagnostic modality in many patients with orthopedic implants such as total joint prosthesis, spinal instrumentation and

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orthopedic plates and screws. However, MRI has largely been avoided in patients with external fixation devices due to reports that have shown significant ferromagnetism of various external fixator components [4, 7, 8]. After a survey of radiologists and radiological technologists, Cannada et al. [7] identified an absence of consensus regarding protocols for scanning patients who had been treated with an external fixator. Thirty-three percent of 30 responding radiologists reported that they had received a request to perform an MRI scan on a patient with a tibial external fixator. Of those radiologists, 69 % agreed to perform the study and reported that 58 % of the scans were of limited or non-diagnostic quality due to image artifacts. The authors further studied artifact production of various external fixators using a phantom model and reported that 13 of 14 fixators tested produced marked or severe artifacts.

The recent advent of newer external fixator components that are non-ferromagnetic and FDA approved as being MRI-safe opens the door for more widespread use of MRI in patients who have been treated with an external fixator. Despite the literature showing their safety, no study has evaluated the potential artifact distortion caused by these newer devices, which may compromise the diagnostic value of the procedure [9, 10]. Furthermore, to our knowledge, no study has quantitatively and qualitatively analyzed specific anatomic structures on MRI images taken in the presence of an external fixator.

The purpose of our study is to evaluate the effect of two popular FDA-approved, MRI-compatible, external fixators on MRI image quality using a cadaveric knee model, where the image quality refers to the ability of an image to retain similar diagnostic qualities as the control with no external fixator present. The clinical question of interest was whether MRI-compatible external fixators produced any significant distortion to the MRI image.

We hypothesized that:

1. MRI images, due to the presence of external fixator, would have lower signal-to-noise ratio.
2. The effect of the noise due to the external fixator would be small enough that it would not obscure the clinical evaluation of the anatomic landmarks of the knee when compared to the control.

Materials and methods

Case design

A cadaveric study was performed to analyze MRI images taken in the presence of two popular brands of external fixator. Cadaveric knee scans taken with and without external fixator present served as specimens, and MRI scans taken without external fixator present served as our controls. Signal-to-noise ratios (SNRs) were measured at five specific anatomic structures and compared as a quantitative measure of image quality. Each scan was also graded according to a five-point scale by three blinded musculoskeletal radiologists focusing on six key structures.

Specimen preparation

An IRB waiver was obtained as the study design consisted of a cadaveric experiment. Seven cadaveric lower extremities (three pairs and one single extremity) were obtained from the anatomy department of our institution ($N = 7$). Each extremity was amputated from its respective cadaver at the level of the proximal femur using a handsaw. The anatomy department keeps detailed records about the medical conditions of each cadaver. Six of the seven cadaver knees had no history of previous surgery, and one had undergone an arthroscopic procedure that was listed as a "removal of cartilage," likely referring to an arthroscopic meniscectomy.

Instrumentations

All specimens were sequentially instrumented with both devices (groups 1 and 2), yielding a paired experimental design.

Group 1

First, all specimens were instrumented with a knee-spanning diamond frame MRI-compatible large external fixation instrumentation (Synthes AO, Paoli, PA). Each frame was constructed using two 5 × 250 mm titanium half-pins in each femur and tibia. The first femoral and tibial half-pin was placed 20 cm above and below the superior and inferior pole of the patella, respectively. The second pin was then placed to fit in the furthest most slot of the large pin-to-pin connecting clamp. The diamond frame was then constructed using four 200-mm carbon-fiber rods with a rod-to-rod connector on each side (Fig. 1).

Group 2

All instrumentation from group 1 was removed, and a new set of identical knee-spanning diamond frame MRI-compatible external fixation instrumentation (Hofmann II, Stryker, Mahwah, NJ) was placed. MRI-safe stainless steel half-pins were used in this group. Similarly sized pins, pin-to-pin and rod-to-rod connectors were utilized compared to the frames in group 1 (Fig. 1).

Fig. 1 Synthes external fixator (*left*), Stryker external fixator (*right*)

MRI scanning

MRI scanning was taken on group 1 and group 2 constructs, respectively. The control group images were obtained after the removal of group 1 instrumentation before the placement of group 2. Therefore, each of the seven cadaveric knees underwent three MRI scans using the standard protocol for knee MRI used at our institution. Each scan included sagittal and coronal PDW (proton density-weighted) sequences with and without fat-saturation and axial PDW fat-saturation sequences taken on a 3.0-T scanner (TrioTim 3T, Siemens, Malvern, PA).

Body coil and knee coil

Given the large size of the fixation frames, the standard knee coil could not be used. Therefore, all scans (including controls) were taken using a standard body array coil. To compare the effect of coil type on noise ratio and image quality, a second control scan was taken on three cadaver knees using a standard knee coil. This resulted in a total of 24 MRI scans, which were taken over a two-day study period.

Data analysis

Signal-to-noise ratio (SNR)

The signal-to-noise ratio at five constant locations was then calculated for each scan [11, 12]. This calculation was performed by a radiology resident (NM) under the supervision of an MRI physicist. The calculation was performed according to the equation $SNR = SI_{Tissue}/SD_{noise}$, where SI_{Tissue} is the region-of-interest (ROI)-based signal intensity and SD_{noise} is the standard deviation of the background noise. Increasing values of SNR indicated less noise in the images.

The five locations of interest included the patellar tendon (PT), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial meniscus (MM) and bone marrow (BM). A circular ROI measuring 17.3 mm^2 was used for the PT on the sagittal PDW fat-suppression sequence; a circular ROI measuring 6.2 mm^2 was used for the MM on the coronal T2 fat-suppression, and a circular ROI measuring 503.2 mm^2 was used for the BM (measured at the distal femoral metaphysis, unless there was irregular signal due to artifact in which the ROI was placed over the proximal tibial metaphysis) on the coronal PDW fat-suppression sequence. The ROI for the ACL and PCL covered the entire structure on a single sagittal slice on the corresponding sagittal PDW fat-suppression sequence.

Image quality analysis

A qualitative analysis was then performed using a five-point grading scale developed by the authors to assess the influence of metal artifact on the quality of the images. Although it is not a previously validated scoring system, it was used in the literature previously [13, 14]. The structures graded were lateral collateral ligament (LCL) and popliteus (P); lateral meniscus (LM); ACL/PCL; MM; medial collateral ligament (MCL); and articular cartilage (AC). The 24 MRI scans were duplicated three times to create a data set of 72 scans which were then graded by three blinded musculoskeletal radiologists using our grading scheme (Table 1). A comparison of grades was made between groups, as well as inter- and intra-observer reliability.

Statistical analysis

Given the nonparametric distribution of this small sample size, a method-specific comparison of SNRs between the body coil control, group 1 and group 2 was made using the Kruskal–Wallis test. The Mann–Whitney test was used for

Table 1 Five-point grading scale for qualitative scoring of images

1. No artifact detected
2. Artifact present but not involving structure of interest
3. Artifact mildly limits evaluation (involves structure of interest, but does not detract from confident interpretation)
4. Artifact limits evaluation (some uncertainty introduced by the artifact)
5. Artifact causes non-diagnostic evaluation

Table 2 SNR comparing control, Stryker and Synthes groups using body coil

	Control		Stryker		Synthes		*p* value*
	Median	(Min–max)	Median	(Min–max)	Median	(Min–max)	
PT SNR	12.9	(5.8–21.4)	5.1	(3.9–28.8)	4.5	(2.8–10.9)	**0.03**
ACL SNR	42.7	(22.5–59.1)	27.8	(8.3–55.9)	19.1	(9.0–39.3)	0.08
PCL SNR	30.1	(18.3–35.4)	21.6	(9.3–38.5)	16.6	(7.4–25.1)	**0.03**
MM SNR	13.2	(7.7–20.4)	7.9	(6.3–25.1)	7.1	(3.4–10.5)	**0.02**
BM SNR	12.8	(7.8–23.0)	13.0	(7.2–15.6)	7.6	(4.7–10.8)	0.05

Bold values indicate statistical significance at $p < 0.05$

* Kruskal–Wallis test

post hoc analysis to compare SNR differences between individual groups and to evaluate differences in SNR between body coil and knee coil controls.

Similarly, the Kruskal–Wallis test was used to evaluate differences in MRI grades based on the radiologists' grading of body coil control, group 1 and group 2 scans. The Mann–Whitney test was used to compare differences in grading between individual groups and between body coil and knee coil controls.

Intra- and inter-grader reliability was analyzed using Goodman and Kruskal's gamma, Cronbach's alpha and the intra-class correlation coefficient (ICC). A value of 0 represents agreement equivalent to that expected by chance, while a value of 1 represents perfect agreement.

An alpha value of <0.05 was used to indicate statistical significance. The statistical analysis was completed using a statistics software (SPSS Inc., Chicago, IL).

Results

There was a statistically significant difference in mean SNR between the body coil control (BC) and the experimental groups for measurements taken at the PT, PCL and MM. At the PT, median SNR was 12.9 (5.8–21.4) for BC, 4.5 (2.8–10.9) for group 1 and 5.1 (3.9–28.8) for group 2 scans ($p = 0.03$). At the PCL, median SNR was 30.1 (18.3–35.4) for BC, 16.6 (7.4–25.1) for group 1 and 21.6 (9.3–38.5) for group 2 scans ($p = 0.03$). At the MM, median SNR was 13.2 (7.7–20.4) for BC, 7.1 (3.4–10.5) for group 1 and 7.9 (6.3–25.1) for group 2 scans ($p = 0.02$). There was no statistically significant difference in median SNR between the three groups for measurements taken at the ACL or BM ($p = 0.08$ and 0.05, respectively) (Table 2).

Post hoc analysis to compare differences in SNR between individual groups showed a statistically significant difference between BC and group 1 scans for measurements taken at the PT, PCL and MM with Z values of −2.75, −2.62 and −2.87, respectively ($p = 0.01$, 0.01, and 0.004, respectively). There was no statistically significant difference in SNR comparisons between the BC and group 2 scans at all locations, between the group 1 and group 2 scans at all locations or between the BC and group 1 scans at the ACL and BM ($p > 0.05$) (Table 3).

Table 3 Post hoc comparison of SNR between groups

	C versus Stryker	C versus Synthes	Stryker versus Synthes
PT SNR	−1.09	**−2.75***	−1.34
ACL SNR	−1.09	−2.24	−1.09
PCL SNR	−1.60	**−2.62***	−0.83
MM SNR	−0.83	**−2.87****	−1.72
BM SNR	−0.70	−1.98	−2.11

Bold values indicate statistical significance at $p < 0.05$

Z values of Mann–Whitney test

* Significant difference: * $p = 0.01$ and ** $p = 0.004$

Table 4 SNRs between body and knee coil controls

	Knee control		Body control		*p* value*
	Median	(Min–max)	Median	(Min–max)	
PT SNR	26.5	(10.5–29.3)	12.9	(5.8–21.4)	0.14
ACL SNR	83.1	(78.9–85.1)	42.7	(22.5–59.1)	**0.02**
PCL SNR	67.7	(55.6–69.5)	30.1	(18.3–35.4)	**0.02**
MM SNR	22.2	(15.4–36.2)	13.2	(7.7–20.4)	0.05
BM SNR	30.5	(24.0–36.3)	12.8	(7.8–23.0)	**0.02**

Bold values indicate statistical significance at $p < 0.05$

* Mann–Whitney test

Comparison of median SNR between the knee coil controls (KCs) and the body coil controls (BCs) showed statistically significant differences at the ACL, PCL and BM ($p = 0.02$). For the KC, median SNR was 83.1, 67.7 and 30.5 at the ACL, PCL and BM, respectively, versus 42.7, 30.1 and 12.8 for the BC ($p = 0.02$). There was no difference in SNR between the KC and BC for measurements at the PT or MM ($p = 0.14$ and 0.05, respectively) (Table 4).

Comparing median MRI image quality scores based on the five-point grading scale, no statistically significant difference was found between the BC, group 1 or group 2.

Table 5 MRI image quality score based on five-point grading scale among control, Stryker and Synthes

	Body control		Stryker		Synthes		p value*
	Median	(Min–max)	Median	(Min–max)	Median	(Min–max)	
LCL and popliteus	2.0	(1.1–2.1)	2.0	(1.4–2.6)	2.2	(2.0–2.2)	0.05
Lateral meniscus	2.0	(1.1–2.0)	2.0	(1.4–2.2)	2.0	(2.0–2.8)	0.05
ACL/PCL	2.0	(1.1–2.1)	2.0	(1.4–2.1)	2.0	(2.0–2.3)	0.23
Medial meniscus	2.0	(1.1–2.1)	2.0	(1.4–2.3)	2.0	(2.0–2.4)	0.19
MCL	2.0	(1.1–2.6)	2.0	(1.4–2.6)	2.0	(2.0–2.7)	0.48
Articular cartilage	2.0	(1.1–2.7)	2.7	(1.4–3.1)	2.6	(2.0–3.4)	0.10
Total MRI score	12.0	(6.7–13.4)	12.9	(8.7–14.7)	13.11	(12.2–15.1)	0.09

* Kruskal–Wallis test

Table 6 MRI image quality score based on five-point grading scale between body and knee coil controls

	Knee coil		Body coil		p value*
	Median	(Min–max)	Median	(Min–max)	
Total MRI score	6.0	(6.0–7.4)	12.0	(6.7–13.4)	**0.03**

* Mann–Whitney test

The median total MRI score was 12.0 (6.7–13.4), 13.1 (12.2–15.1) and 12.9 (8.7–14.7) for the BC, group 1 and group 2, respectively ($p = 0.09$). However, there was a statistically significant difference when comparing median total scores between the KC and BC groups, 6.0 (6.0–7.4) and 12.0 (6.7–13.4), respectively ($p = 0.03$) (Tables 5 and 6).

Goodman and Kruskal's gamma value was calculated to analyze inter-grader reliability between individual radiologists and showed good-to-excellent reliability (gamma 0.65–1), with the highest reliability seen for scoring of both menisci and the cruciate ligaments (gamma 0.95–1). Cronbach's alpha value was used to assess inter-grader reliability between all three radiologists and showed good-to-excellent reliability (alpha 0.66–0.82) (Table 7). Intra-grader reliability was analyzed based on the ICC for all three copies of each scan and showed good-to-excellent reliability. Intra-grader reliability was excellent for IK (ICC 0.95–0.96), excellent for JU (ICC 0.84–0.91) and good to excellent for AC (ICC 0.72–0.94) (Table 7).

Discussion

Quantitative analysis of the noise in the MRI images due to the external fixators through the measurement of SNR showed a significant decrease in SNR of the PT, PCL and MM in the group 1. Qualitative analysis of image quality through a grading system based on the presence of artifact showed no significant difference in the total MRI scans between the control and experimental groups. Thus, all scans were graded as good-to-excellent inter- and intra-grader reliability. These results proved our hypotheses that MRI-safe fixators would not completely eliminate the noise in the MRI signals, but would maintain the diagnostic value of MRI imaging when compared to the controls.

Timely treatment of injury to specific anatomic structure such as posterior lateral corner of the knee is crucial after temporary stabilization of long bone with external fixator. This study may help the orthopedic surgeon to go ahead to order MRI of the injured knee even with external fixator in place. The usage of body versus knee coil is controversial [15–17]. Our study suggested that either one can be used with similar results.

The significant decrease in the signal of the PT, PCL and MM between the control and experimental groups (group 1) may have been produced by the small area, over which the signal was collected, leading to sampling errors and/or an inhomogeneous distribution of signal. The acquisition of signal for the cruciate ligaments and BM was more reliable, as the region of interest was systematically drawn on a single sagittal slice or a larger region of interest was employed to collect maximum signal. The significant increase in the signal of the ACL, PCL and BM in scans with the knee coil compared to the body coil directly reflects this fact and attests to the greater validity of results involving those structures. Knee coil scans produced structures with greater signal because of use of an anatomy-specific coil.

Quantitative and qualitative analysis through the measurement of SNR and a score-based grading scale, respectively, is an established method to assess image quality. Kuhl et al. [14] used comparisons of SNR and a five-point grading scale in analyzing image quality and

Table 7 Inter-grader and intra-grader reliability of MRI scores based on five-point grading scale

Inter-grader reliability			Intra-grader reliability					
	Gamma	*p* value	IK	*p***	JU	*p***	AC	*p***
LCL and popliteus								
IK versus JU	0.95	0.00	0.95	0.00	0.88	0.00	0.72	0.00
IK versus AC	0.65	0.00						
JU versus AC	0.71	0.00						
IK, JU and AC*	0.66							
Lateral meniscus								
IK versus JU	0.95	0.00	0.96	0.00	0.88	0.00	0.84	0.00
IK versus AC	0.99	0.00						
JU versus AC	0.98	0.00						
IK, JU and AC*	0.82							
ACL/PCL								
IK versus JU	0.95	0.00	0.95	0.00	0.91	0.00	0.87	0.00
IK versus AC	1.00	0.00						
JU versus AC	0.97	0.00						
IK, JU and AC*	0.81							
Medial meniscus								
IK versus JU	0.95	0.00	0.95	0.00	0.86	0.00	0.84	0.00
IK versus AC	1.00	0.00						
JU versus AC	0.97	0.00						
IK, JU and AC*	0.77							
MCL								
IK versus JU	0.95	0.00	0.95	0.00	0.84	0.00	0.94	0.00
IK versus AC	0.88	0.00						
JU versus AC	0.83	0.00						
IK, JU and AC*	0.69							
Articular cartilage								
IK versus JU	0.77	0.00	0.95	0.00	0.90	0.00	0.89	0.00
IK versus AC	0.76	0.00						
JU versus AC	0.75	0.00						
IK, JU and AC*	0.72							

* Cronbach's alpha

** Intra-class correlation coefficient

diagnostic confidence in ischemic lesions using diffusion-weighted MRI compared to conventional phase encoding. In another study, Kuhl et al. [13] used SNR, contrast-to-noise ratio and a five-point grading scale to show improved diagnostic confidence in evaluating ischemic lesions with diffusion-weighted MRI at 3.0 T compared to 1.5-T imaging.

A clearly defined grading scale to assess image quality of knee MRI is not available in the literature. Our rubric produced scores that demonstrated statistically proven good-to-excellent intra-observer and inter-observer reliability. The format of our rubric may potentially be extrapolated and applied to assess MRI images of other anatomic sites in the presence of artifact-inducing materials.

According to our five-point grading scale, a score of three or less translated to interpretive confidence in evaluation of a specific intra-articular structure. As six structures were scored for each scan, a total score less than or equal to 18 indicated an excellent diagnostic scan. The worst (highest) mean score of an individual study was 15.11 (average of scores given by three radiologists); therefore, one can conclude that all scans in the data set were of excellent diagnostic quality. Even if one considers the worst individual score given by a single radiologist (18), the scan is still of high diagnostic value according to our scale. As expected, knee coil scans had significantly better (lower) total MRI and median scores for each evaluated intra-articular structure compared to the body coil scans because of use an anatomy-specific coil. This fact attests to the validity of our grading scale and serves as an internal control. Nonetheless, both knee and body coil scans were of high diagnostic value, given that scores for both groups were well below 18. While some may argue that a five-point grading scale is under-described and inadequate for determining image diagnostic quality, we believe that a five-point scale introduces less room for bias by the individual image interpreter compared to a larger grading scale, thus making it better suited for our study.

The composition of the metallic hardware is directly related to the magnitude of artifact. Stainless steel hardware has been reported to produce more inhomogeneity in the local magnetic field and consequently more severe artifact than non-ferromagnetic titanium hardware [15]. Therefore, our finding that there was a decreased SNR in the group 1 is somewhat paradoxical as the group 1 fixator tested used titanium Shanz pins, whereas the group 2 fixator used non-ferromagnetic stainless steel pins. The reduction in SNR may have been due to the composition and/or geometry of other components in the group 1 construct such as the connectors, clamps or rods.

A significant limitation of the study is the small sample size, making it difficult to pick up small differences between the control and experimental groups. Triplicating the 24 scans evaluated by the musculoskeletal radiologists was an attempt to counter the effect of small sample size. A second limitation was the use of cadaver extremities, which, at best, only mimic physiologic signal of the intra-articular structures evaluated. Smaller structures were frequently inhomogeneous due to microscopic edema infiltrating the non-living tissue and were more difficult to evaluate quantitatively as ROIs collected signal over smaller areas. This may explain the lower SNR seen in the group 1.

Future investigation may focus on measuring diagnostic accuracy in evaluating intra-articular structures on MRI of the knee in patients with external fixators who undergo knee arthroscopy, which is a strong tool to confirm or rule out the presence of pathology. MR sequences may be further optimized to suppress artifact through techniques such as increasing receiver bandwidth and use of STIR as opposed to fat-suppression sequences. A similar study design to ours may also be applied to living human subjects for more physiologic results.

In conclusion, MRI images of the knee in the presence of the two MRI-compatible external fixators showed that these new devices did not fully eliminate the noise from the MRI images. However, despite the reduction in SNR detected, all scans were considered to have good image quality, which may allow easy diagnosis of any pathology in the presence of these external fixators as evaluated by three musculoskeletal radiologists.

Conflict of interest Authors declare no conflict of interest.

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