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ORIGINAL ARTICLE

Safety and image quality of MR-conditional external fixators for 1.5 Tesla extremity MR

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Abstract

Purpose To evaluate the safety and image quality of extremity MR examinations performed with two MR conditional external fixators located in the MR bore.

Materials and methods Single-center retrospective study of a prospectively maintained imaging dataset that evaluated MR examinations of extremities in patients managed with external fixations instrumentation and imaged on a single 1.5T MR scanner. The fixation device was one of two MR-conditional instrumentation systems: DuPuy Synthes (aluminum, stainless steel, carbonium and Kevlar) or Dolphix temporary fixation system (PEEK-CA30). Safety events were recorded by the performing MR radiologic technologist. A study musculoskeletal radiologist assessed all sequences to evaluate for image quality, signal- and contrast-to-noise ratios (SNR/CNR), and injury patterns/findings.

Results In the 13 men and 9 women with a mean age of 42 years (range 18 to 72 years), most patients (19/22 patients; 86%) were involved with trauma resulting in extremity injury requiring external fixation. MR examinations included 19 knee, 2 ankle, and 1 elbow examinations. There were no adverse safety events, heating that caused patient discomfort, fixation dislodgement/perturbment, or early termination of MR examinations. All examinations were of diagnostic quality. Fat-suppressed proton density sequences had significantly higher SNR and CNR compared to STIR (p = 0.01 to 0.04). The lower SNR of STIR and increased quality of fat-suppressed proton density during the study period led to the STIR sequence being dropped in standard MR protocol.

Conclusion MR of the extremity using the two study MR conditional external fixators within the MR bore is safe and feasible.

Keywords MR safety · External fixator · MR artifact · Susceptibility artifact · Tibial plateau fracture

Introduction

Ligamentous, tendons, menisci, and other non-osseous injuries associated with intra-articular fractures can change operative approaches if imaged prior to definitive repair or conservative management [1, 2]. The mainstay of orthopedic trauma imaging is with radiographs with selected use of computed tomography (CT); however, magnetic resonance (MR) imaging can provide better diagnostic information about tendinous, ligamentous, and meniscal injuries and other findings that may affect management [3, 4]. External fixators are often used to temporize unstable fractures and their presence may preclude some centers from performing MR [5, 6]. Many commercially available external fixators are designated as MR conditional as they are made of nonferromagnetic materials such as titanium, composite of stainless steel, carbon fiber reinforced polymers, and others. Some of these external fixators have undergone approval processes for MR-conditional, the highest FDA designation for MR safety for metallic implants [5]. MR conditional items are those that have data supporting that they pose no known hazards in an MR environment at specified conditions, including static magnetic field strength, radiofrequency fields, specific absorption rate, and other parameters [7, 8].

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A number of translational studies using MR to image phantoms with commercial external fixators made of various materials have been performed [9–12], focused on magnetic attraction [10], heating [11, 12], and presence of fixators and signal-to-noise ratios (SNRs) [9]. Few prior clinical cohorts with modern external fixators in the MR gantry have ranged from few patients to 57 patients using various commercial external fixators [5, 13]. Although screw depth [8] and the degree of magnetic attraction [9] both influence heating of the fixator, the incidence of adverse safety events in clinical series has been low (0–4%) [5, 13]. The presence of external fixators has been shown to significantly lower objective measurements of SNR in tendons, ligaments, and menisci of cadaveric knees [9]. That same cadaver study [11] showed that presence of external fixators did not significantly affect radiologists' subjective grading of visualizing key anatomic structures of the knee [9]; however, they did not assess pathologic conditions. Prior clinical series [5, 13] have evaluated safety events with MR imaging of external fixators but have not objectively assessed image quality. A dated study by Cannada et al. [6], published in 1995, surveyed radiologists and assessed their comfort level in performing MR in patients with external fixators. In this dated survey, 63% (19/30) respondent radiologists and 71% (26/37) of the radiological technologists were comfortable performing MR examinations with external fixators [6]; to the best of our literature search, no more recent data surveying radiologists and technologists has since been published. Our orthopaedic surgeons have increased the institutional volume of performing MR while patients are temporized with external fixation using one of two commercial devices of differing materials, constituting the basis for the present study. The purpose of this study was to evaluate the safety and image quality of extremity MR examinations performed with MR conditional external fixators located in the MR bore.

Materials and methods

This was an Institutional Review Board-approved, HIPAA-compliant single-center level I trauma center retrospective study of a prospectively maintained database. The need to obtain informed consent was waived. All MR examinations performed in adult patients (> 18 years old) with MR-conditional external fixators in the MR bore during a 24-month study period were queried for potential inclusion. Inclusion criteria were patients with extremity fractures managed with external fixators who underwent joint MRs with the fixators in the MR bore and had available orthopedic follow-up with subsequent surgical management. Such MRs were performed to assess for ligament, tendon, meniscal, and soft tissue injuries that would influence subsequent open reduction and internal fixation. Exclusion criteria included patients who underwent joint MR with external fixators not in the MR bore; for example, a patient who had a knee external fixator but underwent an MR of the ankle would not be included. Cases were reviewed for safety events including early termination of the examination due to patient-reported heating. A study musculoskeletal radiologist assessed image quality and injury patterns.

The fixation device in all cases were one of two MR-conditional external fixation systems: DuPuy Synthes external fixators (Johnson and Johnson, Warsaw, Indiana; made primarily with aluminum, stainless steel, carbonium and Kevlar, or Dolphix temporary fixation system (CiTiEffe srl, Calderara di Reno, Bologna, Italy) made of Ketron Peek CA30, a semi-crystalline polymer based on polyetheretherketone resin loaded with 30% carbon fibers. These were fixated with standard titanium pins.

MR acquisition

All examinations were performed on a single GE Signa at 1.5 Tesla system (GE Healthcare, Chicago, IL) without intravenous contrast unless there was concern for osteomyelitis with long indwelling instrumentation. Standard MR acquisition is demonstrated in Table 1. Of note, PDFS sequences were performed with an intermediate TE (TE of 40 ms [Table 1]). Coils included cardiac, torso, or knee coils. Coils were chosen to fit the bulk of the fixator apparatus. The performing MR technologist was instructed to record safety events including patient reported heating and early termination due to patient discomfort. After the MR examination was ended, the orthopedic surgeon (resident or attending) involved in clinical care assessed the configuration of the external fixation instrumentation to assess for any displacement and perturbation.

Image evaluation

All study examinations were interpreted by a musculoskeletal trained radiologist with more than 20 years of musculoskeletal MR experience (AAS). The radiologist had access to correlative imaging and patient age and sex were not blinded. The radiologist was blinded to any subsequent surgical findings. When correlative CT was available that imaging examination was also interpreted by the study radiologist. The radiologist graded each sequence with a binary scoring scale of diagnostic and nondiagnostic. Diagnostic was defined as sufficient quality, signal, and lack of artifact obscuring findings at or near the joint. Nondiagnostic was defined as any factor that obscured evaluation at or near the joint.

Signal-to-noise ratio (SNR) calculations were performed for knee MR acquisition comparing proton density fat saturation (PDFS) and short tau inversion recovery (STIR) sequences. For homogeneity of data and analyses, the non-knee MR examinations included in this study did not have an objective SNR calculation. SNR was calculated from a single slice. Tissue

Table 1 Standard MR protocol for joints imaged in external fixators

	Axial proton density fat saturation	Coronal proton density	Coronal proton density fat saturation	Sagittal proton density	Sagittal proton density fat saturation	Sagittal short tau inversion recovery (STIR)*
Field-of-view (cm):	18	20	20	20	20	18
Pixel Spacing (mm/mm):	0.352/0.352	0.391/0.391	0.391/0.391	0.391/0.391	0.391/0.391	0.703/0.703
Receiver bandwidth (mHz)	15	50	15	50	15	15
Repetition time/TR (ms)	2200	2500	2117	2500	2117	3000
Echo time/TE (ms)	40	15	40	15	40	50
Slice Thickness (mm)	5	4	4	4	4	4
Slice Spacing (mm)	1	1	1	1	1	1
Matrix	320 × 224	320 × 256	320 × 224	320 × 256	320 × 224	320 × 224

* Note the STIR was eventually dropped from the standard MR protocol due to noisy/grainy appearance

mean signal intensity and standard deviation were measured with a circle shaped ROI 100 mm^2 in size in distal femur bone marrow at the level of the ACL. Noise mean signal intensity and standard deviation were measured with a circle shaped ROI 100 mm^2 in size in the air adjacent to knee joint at the level of the ACL. Measurements were made on sagittal acquisitions. Two SNR calculations were performed using the following formulas: SNR = SI_{Tissue}/SD_{Tissue} ($SNR_{T/T}$) and SNR = SI_{Tissue}/SD_{Noise} ($SNR_{T/N}$). Contrast-to-noise ratio (CNR) was also calculated from the following formula: CNR = $(SI_{Tissue}-SI_{Noise})/SD_{Noise}$

Data were summarized with descriptive statistics. Chi-squared analysis was used to compare for differences between MR sequences and the two brands of external fixators. Two-tailed Student *t* test was used to compare the SNRs and CNRs.

Results

Patient characteristics

Twenty patients including 12 men and 8 women with a mean age of 42 years (range 18 to 72 years) were included. Most patients (19/22 patients; 86%) were involved with trauma resulting in extremity injury requiring external fixation. Of these, 17 placements were primary fracture fixations, one was a revision external fixation, and one was post removal of infected internal fixation instrumentations. Three patients had injury mechanisms secondary to same-level falls. MR examinations of the injured extremities included examinations of the knee, 19 patients, ankle, 2 patients, and elbow, 1 patient.

During the study period, PDFS sequences were noted to provide comparable diagnostic information compared to STIR sequences. Accordingly, PDFS was used as the standard fat saturation sequence and STIR was dropped from the standard acquisition (STIR performed overall in 6 of 22 examinations, 27%, and 5 of 19 knee MR examinations, 26%). With the exception of one examination where internal fixation instrumentation was previously removed due to infection, all other examinations were acquired without intravenous contrast (21 of 22 [95%] noncontrast examinations). Coils were used that fit the extremity and fixator apparatus and included a cardiac coil in most cases (18 of 22; 82%), along with knee coils (3 of 22; 14%) and torso coil (1 of 20; 5%) in additional cases.

There were no adverse safety events, heating that caused patient discomfort, fixation dislodgement/perturbment, or early termination of MR examinations. All examinations were of diagnostic quality and all imaging sequences were rated diagnostic-good quality without significant difference (p = 1.00). Case examples are illustrated in Figs. 1 and 2. There was no significant difference between the examination diagnostic quality between the DuPuy Synthes (n = 6 patients) or Dolphix fixator (n = 16 patients) (p = 1.00); however, in one examination that used both PDFS and STIR, a medial meniscus tear was seen on PDFS and not on STIR (Fig. 1). The marginal SNR of STIR during the study period led to the sequence being dropped in the standard MR protocol (STIR performed in 6 of 22 examinations) and PD fat saturation served as the standard fat suppression technique.

Proton density fat-suppressed sequences had significantly higher SNR compared to STIR in all comparisons (p = 0.01 to 0.04). Mean $SNR_{T/T}$ for the 14 knees with PDFS was 8.6 (± 2.2), which was significantly higher than the 5 STIR knee examinations mean $SNR_{T/T}$ of 6.1 ± 0.6 (p = 0.01). The comparison was similar for the $SNR_{T/N}$ with a mean $SNR_{T/N}$ for the 14 knees with PDFS of 13.8 (± 6.2), which was significantly higher than the 5 knees with STIR mean $SNR_{T/N}$ of 8.5 (± 2.2) (p = 0.04). CNR in PDFS was significantly higher for PDFS compared to STIR (8.6 ± 6.1 for PDFS vs 3.0 ± 2.4 for STIR) (p = 0.03).

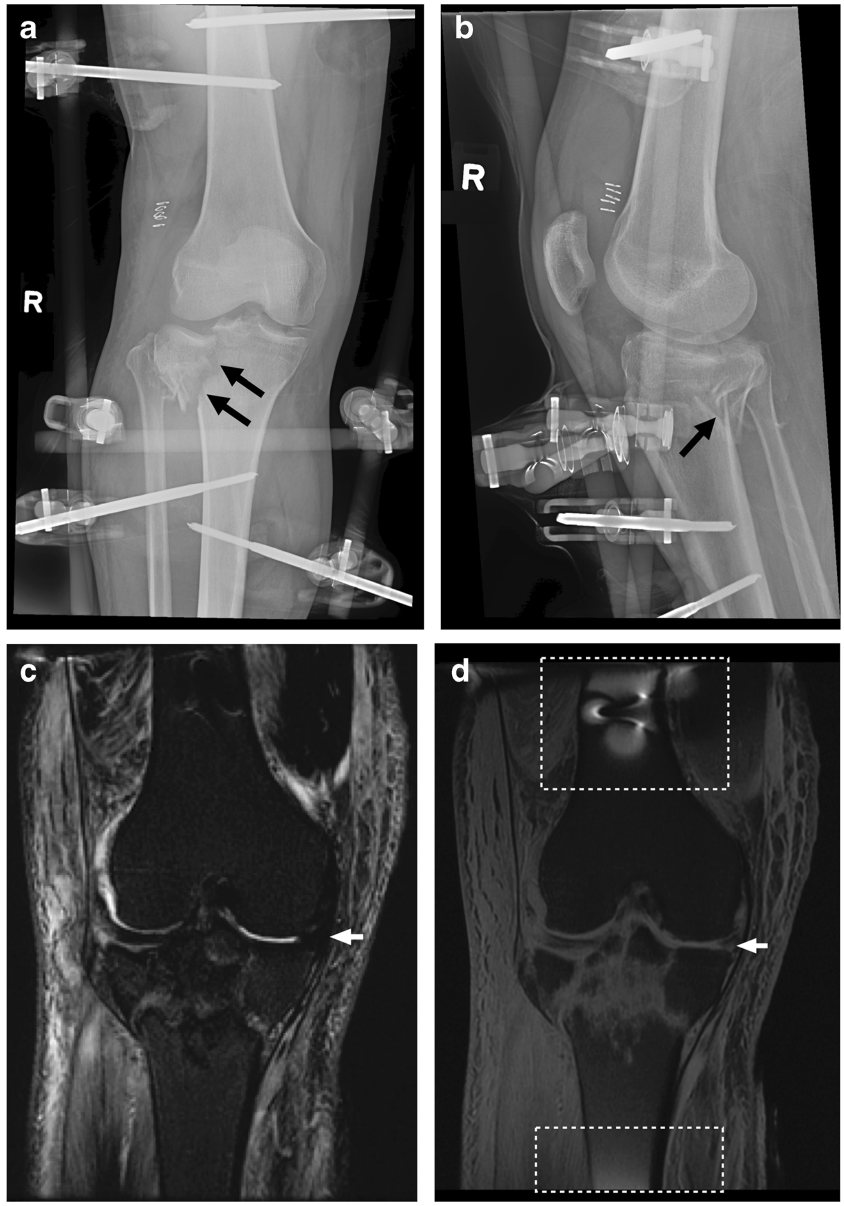
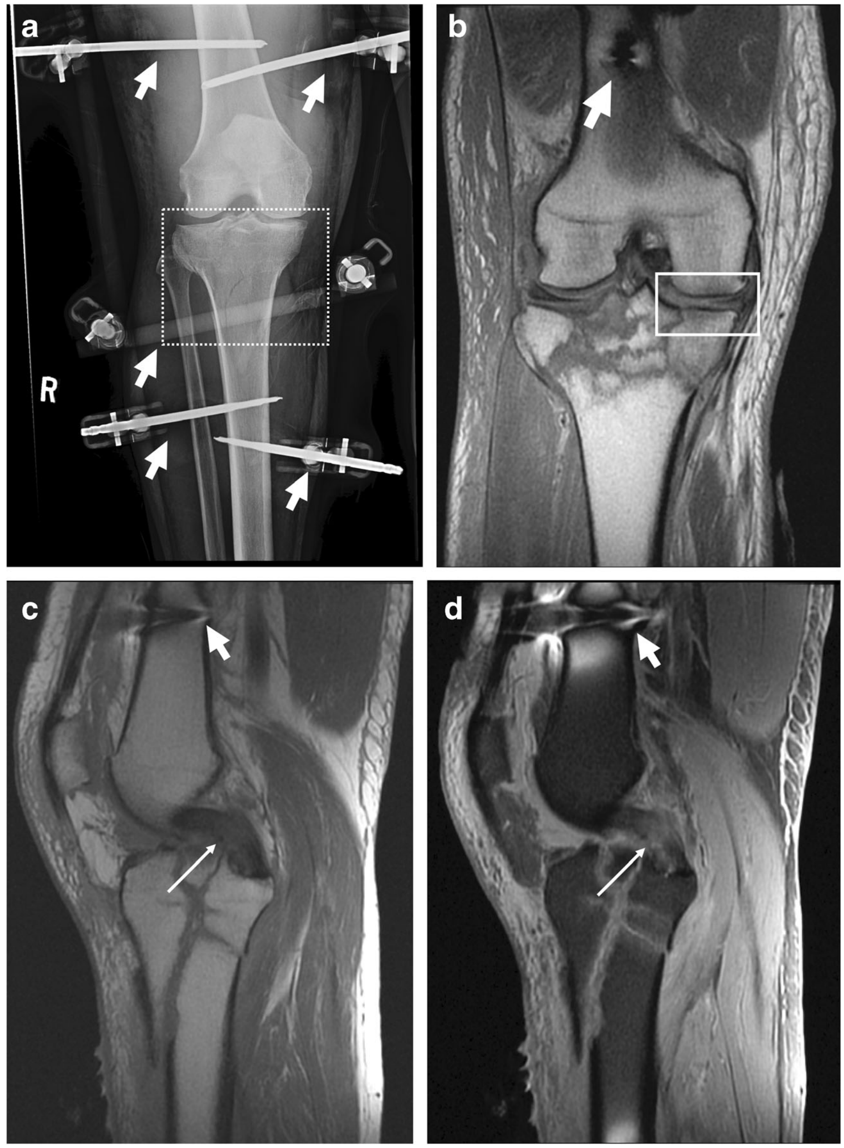


Fig. 1 Image quality of STIR vs proton density. MR performed after external fixation of Schatzker V tibial plateau fracture to assess for associated injuries. **a**, **b** Frontal (**a**) and lateral (**b**) right knee radiographs demonstrate the lateral component of the tibial plateau fracture (dashed arrow) along with a moderate sized lipohemarthrosis and delineate the numerous titanium external fixation pins anchored to the femur and tibia. **c**–**d**. Coronal STIR (**c**) and fat-saturated proton density (**d**) MR acquisitions. Although proton density is more prone to susceptibility artifact (dashed boxes), the finding of a medial meniscus tear is only well seen on proton density and not STIR (solid arrow)

When comparing PDFS signal characteristics with knees fixated by either the Dolphix (n = 9) or Synthes (n = 6) systems, mean PDFS $SNR_{T/T}$ for the 9 knees fixated with Dolphix was 9.5 ($\pm$ 2.1), which was significantly higher than the 5 knees fixated with Synthes with a mean PDFS $SNR_{T/T}$ of 7.0 $\pm$ 0.9 (p = 0.02). Although PDFS $SNR_{T/N}$ was higher in knees fixated with Dolphix compared to Synthes (15.4 $\pm$ 6.6 vs. 10.8 $\pm$ 3.0, respectively), this did not achieve statistical significance (p = 0.10). CNR similarly had a higher mean value in knees fixated with Dolphix compared to Synthes but was not significantly different (10.1 $\pm$ 6.5 vs. 5.7 $\pm$ 3.0, p = 0.10).

Most patients had CT preceding the external fixation placement (16 of 22 overall and 16 of 19 with knee injuries). In these 16 CT examinations of the knee, 11 had tibial plateau fractures (Schatzker III = 1 patient, Schatzker V = 5 patients; Schatzker VI = 5 patients), 1 patient had a knee dislocation; and 4 patients had no fracture about the knee. On MR, ligamentous injuries included anterior cruciate (partial to full thickness tear or avulsion) (n = 10 of 19 [53%] patients with knee injuries), posterior cruciate (partial to full thickness tear or avulsion) (n = 11 of 19 [58%] patients with knee injuries), medial collateral (partial to thickness tear or avulsion) (n = 10 of 19 [53%] patients with knee injuries), and lateral collateral ligament (full thickness tear or avulsion) (n = 4 of 19 [21%] patients with knee injuries). Meniscal injuries included 5 medial meniscus tears and 6 lateral meniscus tears. Imaging findings in the two ankle MRs included noncontrast and contrast manifestations of fibular osteomyelitis in one patient and injures including anterior talofibular, posterior talofibular,

Fig. 2 Local susceptibility artifact from external fixators. Sixty-three-year-old man ejected from a motor vehicle collision resulting in right-sided Schatzker V tibial plateau fracture. **a** Frontal radiograph of the right knee demonstrates the right tibial plateau fracture (dashed box) along with the multiple titanium external fixator pins and constructs spanning the knee and anchored to the femur and tibia (thick arrows). In the coronal (**b**) and sagittal (**c**) proton density along with fat-suppressed sagittal proton density acquisitions, note the susceptibility artifact signal void of the external fixation device in the field of view (thick arrows); note how this results in localized failure of fat suppression in **d**. Injuries included tear of the posterior horn of the medial meniscus (**b**, solid box) and tear of the posterior cruciate ligament (**c** and **d**, thin arrows)



calcaneofibular, and deltoid ligament tear. Injuries in the one elbow examination included lateral collateral ligament tear and tears of common flexor and extensor tendons. Although not objectively evaluated in each study, a number of ligaments associated with complex fractures demonstrated laxity without tear due to displaced bone fracture fragments, but without associated ligament injury (case example in Fig. 3). One case demonstrated fracture lines continuous with adjacent ligament and tendon tears (case example in Fig. 4).

Discussion

The present study primarily demonstrates that no safety events occurred, including heating or pain (patient-reported) that caused the examination to be aborted along with no perturbment or movement of the fixation devices. Additionally, our protocol dynamically changed during the study period with STIR resulting in diagnostic acquisitions, but of lower SNR. Fat-suppressed proton density sequences had significantly higher SNR, but moreover provided diagnostic images without suffering from joint-centered artifacts that precluded diagnostic evaluation. This led to a change in our MR protocol with external fixation devices in the MR bore where STIR was dropped in favor of fat-suppressed proton density serving as the fat suppression sequence of choice. STIR is usually performed with indwelling metal instrumentation due to less susceptibility and more uniform fat suppression and with a known decrease in SNR [14]. The localized failure of fat suppression seen with proton density acquisitions was not a substantial factor, as the indwelling instrumentation was well away from the joint and focus of the imaging acquisition. A number of ligamentous and meniscal injuries were reported, predominantly associated with knee injuries (patient with knee MRs constituted 19 of 22

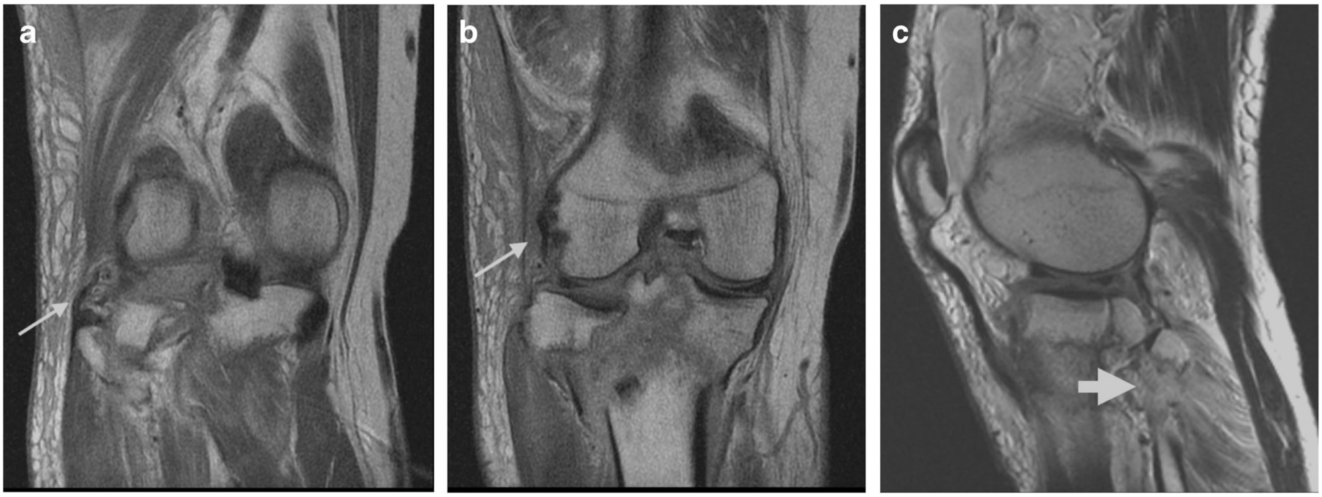


Fig. 3 Injury patterns in complex fracture. Forty-nine-year-old man with a fall from approximately 3 ft resulting in right-sided proximal fibular and Schatzker V tibial plateau fractures, managed with titanium external fixation instrumentation. Proton-density coronal (**a** and **b**) and sagittal (**c**) MR acquisitions demonstrate diffuse laxity and wavy trajectory of the lateral collateral ligament (thin arrows in **a** and **b**) secondary to a displaced fibular head fracture (thick arrows in **c**). Despite this laxity and wavy appearance of the lateral collateral ligament, there was no intrinsic signal disruption to indicate tear and the ligament was confirmed to be intact at surgery

patients). This work delineated unusual injury patterns, such as fracture extending into ligament and tendon tears, and ligament laxity due to displaced fracture fragments, but without associated ligament injury. Identification of these injuries helped the orthopaedic surgeons with their operative approach.

Hayden et al. (13) reported a pooled cohort from four trauma centers with 12 patients with external fixators inside the MR bore and 27 patients with external fixators outside the MR bore. Gillig et al. [5] reported a larger series than the present study, and to the best of our literature search the largest patient cohort of external fixators imaged with MR. In 56 patients, they performed 57 MR acquisitions using patients with tibial plateau fractures fixated with the DePuy Synthes fixators. They reported two safety events (2 of 57 MR examinations; 4%) due to heating and pain/pulling sensation (one case each). Although the present series is smaller with 20 patients and predominantly composed of knee examinations (19 of 22 patients), our study evaluated primarily a different fixation device made of PEEK-CA30 (Dolphix fixation = 16 patients; DePuy Synthes = 6 patients). Additionally, we report associated imaging findings and offer a practical approach of dynamically changing our MR protocol during the study period (dropping the STIR acquisitions).

MR variables that can be manipulated to reduce susceptibility artifact include increasing receiver bandwidth, increasing matrix size, shorter interecho spacing, decreasing slice thickness, and imaging at lower field strengths (e.g., 1.5T instead of 3.0T) [14, 15]. To increase the receiver bandwidth substantially or decrease the slice thickness both decreases the metallic artifact at the expense of decreasing SNR. In the present series, we decided not to modify either the bandwidth or slice thickness because there was already signal loss with using predominantly cardiac/body coils instead of dedicate knee coils. We did not increase the matrix size in this fixator-focused protocol in order to keep the MR examination as short as possible as these patients were often admitted due to polytrauma.

STIR has a more uniform fat saturation compared to frequency-selected fat saturation that is used with PDFS, but at the expense of decreased SNR [14]. We opted to drop STIR from our standard acquisition with external fixators because the fat suppression with PDFS was adequate. The location of the pins was distant enough to obtain good fat suppression that did not interfere with imaging the joints and PDFS resulted in significantly increased SNR. The advantage of proton density sequence evaluation of the menisci was an additional advantage of PDFS over STIR. To further optimize the signal characteristics of PDFS, we used a fat saturation technique with an intermediate TE of 40 ms instead of traditional fat saturations values of 10-20 ms. This intermediate TE is short enough to maintain good signal, yet long enough to be more fluid sensitive.

Limitations include the retrospective nature of this prospectively maintained database and data from a single institution. Image quality and SNR were assessed but not compared to MR of joints without external fixators as a control. Although the examinations were of diagnostic quality from the study radiologist's assessment, assessing the diagnostic assessment of structures such as the menisci compared to MR acquisitions without fixators would be a useful design in future studies. MR findings were correlated with operative findings but reporting and direct objective measures with matching the operative and imaging findings is beyond the scope of this study. Prior in vitro studies have documented temperature

Fig. 4 Ligament and tendon injuries extending into fracture. Forty-two-year-old man who was an unrestrained driver in a motor vehicle collision. Frontal radiograph of the left knee demonstrates a complex Schatzker VI tibial plateau fracture which extend into the intercondylar eminence (box) along with external fixators. Proton-density fat-suppressed sagittal (**b**), coronal (**c**), and axial (**d**) sequences demonstrate partial thickness tears affecting the anterior (black dashed arrow, **b**) and posterior (thin white arrows, **b** and **c**) cruciate ligaments along with the patellar tendon (thick white arrows, **b** and **d**). Note that the posterior cruciate ligament tear and the patellar tendon tear are continuous with associated fracture lines. This is demonstrated in the coronal acquisition (**c**) for the posterior cruciate ligament tear-fracture continuum (thin white arrows) and in the axial acquisition (**d**) for the patellar tendon tear-fracture continuum (thin white arrows)

change and number of other factors [9–12]. This was not assessed but was reflective of our clinical practice. The heterogeneity of the patient cohort is reflected in the 3 different joints images (knee, ankle, and elbow; vast majority knee [19 of 22 patients]) along with the 16 Dolphix and 6 Synthes, although previously mentioned prior patient cohort evaluated more patients with the Synthes fixator [5] compared to present study. Despite these heterogeneous factors, the merit of the present study in part is the evaluation of the Dolphix commercial implant, which to the best of our literature search has not been previously reported in a patient cohort. Comparing these imaging qualities between these two systems, there was no significant subjective difference in image quality. While the knees fixated with the Dolphix system had significantly higher SNR on PDFS compared to the Synthes fixator by the $SNR_{T/T}$ calculation method, there was no significant difference in SNR between n the two systems using the $SNR_{T/N}$ calculation method. The imaging interpretation effect of the SNR differences (in one of the two methods) is unclear, if any. Although there was no significant difference in the imaging quality between the two fixators, future investigations can perform different methods of quantifying SNR and surrogates of signal loss, such as quantifying the failing of fat saturation around the fixator. Furthermore, future studies with more than two commercial fixator systems may be helpful in determining fixator's material composition and its effect on MR image quality.

In conclusion, MR of the extremities with two commercial external fixators was safe and feasible in the present cohort. Evaluation of the MR protocol changed throughout the study period, reflective of the diffuse noise and grainy appearance of STIR acquisitions, in favor of fat suppressed proton density serving as the fat suppression technique of choice. In our experience, STIR's more uniform fat suppression is not relevant for joint MRs with external fixators well away from the ligaments and tendons of relevance for the MR examinations.

Performing MR examinations in complex fractures temporized and managed by external fixators provides valuable preoperative information for the surgeon, identifying non-osseous associated injuries and allowing for patient-specific operative approaches.

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Compliance with ethical standards

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

Ethical approval This was an Institutional Review Board-approved, HIPAA-compliant single-center retrospective study.

Informed consent The need to obtain informed consent was waived.

References

1. Cinque ME, Godin JA, Moatshe G, Chahla J, Kruckeberg BM, Pogorzelski J, LaPrade RF (2017) Do tibial plateau fractures worsen outcomes of knee ligament injuries? A matched cohort analysis. Orthop J Sports Med 5:2325967117723895. https://doi.org/10.1177/2325967117723895
2. Delamarter RB, Hohl M, Hopp E (1990) Ligament injuries associated with tibial plateau fractures. Clin Orthop Relat Res 226–233
3. Karantanas AH (2014) What's new in the use of MRI in the orthopaedic trauma patient? Injury 45:923–933. https://doi.org/10.1016/j.injury.2014.01.012
4. Yacoubian SV, Nevins RT, Sallis JG, Potter HG, Lorich DG (2002) Impact of MRI on treatment plan and fracture classification of tibial plateau fractures. J Orthop Trauma 16:632–637. https://doi.org/10.1097/00005131-200210000-00004
5. Gillig JD, Goode RD, Campfield B, Crim JR, Crist BD (2018) Safety and complications associated with MRI-conditional external fixators in patients with tibial plateau fractures: a case series. J Orthop Trauma 32:521–525. https://doi.org/10.1097/BOT.0000000000001246
6. Cannada LK, Herzenberg JE, Hughes PM, Belkoff S (1995) Safety and image artifact of external fixators and magnetic resonance imaging. Clin Orthop Relat Res:206–214
7. Shellock FG, Woods TO, Crues JV (2009) MR labeling information for implants and devices: explanation of terminology. Radiology 253:26–30. https://doi.org/10.1148/radiol.2531091030
8. Tsai LL, Grant AK, Mortele KJ, Kung JW, Smith MP (2015) A practical guide to MR imaging safety: what radiologists need to know. Radiographics 35:1722–1737. https://doi.org/10.1148/rg.2015150108
9. Elsissy P, Akpolat YT, Chien A, Cheng WK (2015) MRI evaluation of the knee with non-ferromagnetic external fixators: cadaveric knee model. Eur J Orthop Surg Traumatol 25:933–939. https://doi.org/10.1007/s00590-015-1655-9
10. Davison BL, Cantu RV, Van Woerkom S (2004) The magnetic attraction of lower extremity external fixators in an MRI suite. J Orthop Trauma 18:24–27. https://doi.org/10.1097/00005131-200401000-00005
11. Liu Y, Shen J, Kainz W, Qian S, Wu W, Chen J (2013) Numerical investigations of MRI RF field induced heating for external fixation devices. Biomed Eng Online 12:12. https://doi.org/10.1186/1475-925X-12-12
12. Huang X, Zheng J, Wu X, Kono M, Hozono H, Kainz W, Yang F, Chen J (2015) MRI Heating reduction for external fixation devices using absorption material. IEEE Trans Electromagn Compat 57:635–642. https://doi.org/10.1109/TEMC.2015.2407318
13. Hayden BL, Theriault R, Bramlett K, Lucas R, McTague M, Bedi HS, Flacke S, Weaver MJ, Marcantonio AJ, Ryan SP (2017) Magnetic resonance imaging of trauma patients treated with contemporary external fixation devices: a multicenter case series. J Orthop Trauma 31:e375–e380. https://doi.org/10.1097/BOT.0000000000000954
14. Hargreaves BA, Worters PW, Pauly KB, Pauly JM, Koch KM, Gold GE (2011) Metal-induced artifacts in MRI. AJR Am J Roentgenol 197:547–555. https://doi.org/10.2214/AJR.11.7364
15. Farrelly C, Davarpanah A, Brennan SA, Sampson M, Eustace SJ (2010) Imaging of soft tissues adjacent to orthopedic hardware: comparison of 3-T and 1.5-T MRI. AJR Am J Roentgenol 194:W60–W64. https://doi.org/10.2214/AJR.08.1740