Original Research

The use of slice encoding for metal artifact correction (SEMAC) sequencing improves the diagnostic evaluation of graft integrity following anterior cruciate ligament reconstruction

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Metal artifact reduction sequencing (MARS)
Magnetic resonance imaging (MRI)

ABSTRACT

Objectives: To determine whether magnetic resonance imaging (MRI) with metal artifact reduction sequencing is superior to conventional knee MRI in the evaluation of an injured anterior cruciate ligament (ACL) graft, where visualisation on conventional MRI can be limited by the metal artifact from fixation devices.

Methods: Eighteen patients underwent conventional MRI sequence (proton density fat saturated [PDFS]) and two types of metal artifact reduction sequencing MRI (WARP, slice encoding for metal artifact correction (SEMAC); Siemens) following a secondary injury to their ACL reconstructed knee. Six raters with experience in knee MRI evaluation reviewed sagittal PDFS, WARP, and SEMAC sequences, providing semi-quantitative grades for visualisation and diagnostic confidence assessing the ACL, posterior cruciate ligament, menisci, tibial and femoral tunnel margins, and articular cartilage. Intra-class correlation coefficients for inter-rater reliability were evaluated. The 6-rater mean scores for the visualisation and diagnostic confidence derived from each sequence were compared using the Friedman test for multiple paired samples.

Results: No statistically significant difference in the ACL visualisation among the sequences was found (p = 0.193). Further, a subgroup analysis was performed in cases evaluated as “moderately blurry” or “indistinct ACL visualisation” on PDFS (58% of cases). SEMAC significantly improved diagnostic confidence in ACL visualisation (p = 0.041) and ACL graft rupture (p = 0.044) compared to PDFS. There was no statistically significant difference in the inter-observer reliability between sequences. The WARP sequence added 2.84 ± 0.69 min, while SEMAC added 2.95 ± 0.40 min to the standard knee MRI scan time.

Conclusion: Use of the SEMAC metal reduction sequence significantly improved diagnostic accuracy and confidence in the detection of ACL graft rupture in cases where the ACL was moderately blurry or indistinct on the PDFS sequence. This sequence should be considered as an adjunct to conventional PDFS in cases where graft visualisation is limited by the metal artifact from fixation devices.

Level of evidence: III.

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What are the new findings

- The use of slice encoding for metal artifact correction (SEMAC) sequencing improves the diagnostic evaluation of graft integrity following anterior cruciate ligament reconstruction.
- Metal artifact reduction sequencing aids in the diagnosis of a graft rupture and the evaluation of a previous tunnel position providing important information for surgical planning of a revision surgery.
- A novel diagnostic algorithm is provided for the use of metal artifact reduction sequencing as an adjunct to conventional magnetic resonance imaging sequences in evaluating the integrity of the anterior cruciate ligament graft following re-injury in the acute injury phase or when clinical assessment is equivocal.

1. Introduction

The anterior cruciate ligament (ACL) is the most frequently reconstructed knee ligament, with 80% of knee ligament surgeries involving the ACL [1,2]. The rate of ACL reconstruction (ACLR) continues to increase. In the United States, there was a 37% increase in surgeries from 1994 to 2006, representing an increase of 134,421 ACLR annually [3].

Magnetic resonance imaging (MRI) is the current gold standard imaging modality in the diagnosis of a native ACL tear [4]. In the native knee, MRI has a diagnostic accuracy of 83%–95% sensitivity and 95%–100% specificity for native ACL tears, and has a well-defined role in identifying meniscal tears and cartilaginous injuries [5].

Registry data indicate that close to 60% of ACLR occurs in the young, active population between the ages 15–29 [6]. Many techniques for ACLR exist, all requiring some form of implant for graft fixation. Metallic implants such as interference screws, cortical buttons, and staples are some of the most common implants used [7]. It can be difficult to ascertain the integrity of the reconstructed ACL graft vis-a-vis stress relaxation, complete ruptures, partial ruptures, or fixation failure. Rates of ACL graft rupture are 3.9–11.1%, with an overall graft rupture rate of 7.9% at a minimum follow-up time of 10 years, as indicated in a systematic review by Magnusson et al. [8]. Advanced imaging studies, particularly MRI, can assist in confirming a graft rupture, identifying causes of failure, associated injuries, and planning a revision surgery. Complications following ACLR that can be seen at MRI include cyclops lesion, graft impingement, graft rupture, and tunnel widening [9].

An MRI assessment of ACL graft integrity following ACLR is challenging. Signal changes related to the ligamentisation process of the ACL graft may be confused with partial or even complete graft rupture [9]. A magnetic susceptibility artifact can distort or obscure the graft and tunnels. This artifact is not only due to metal implants but also to microscopic metallic debris remaining in the joint and tunnels following surgery [9–12,16]. This can lead to a limited diagnostic value with MRI when evaluating graft integrity, which presents a diagnostic problem when trying to evaluate patients who have suffered another injury to their surgically reconstructed knee [9,10,12]. Imaging accuracy can be improved by noting secondary signs of ACL graft rupture such as anterior tibial translation, uncovered posterior horn of the lateral meniscus, posterior cruciate ligament (PCL) hyperbuckling, and an abnormal PCL line [13]. However, ideally, the ACL graft would be clearly visualised using MRI despite metal artifacts.

Metal artifact reduction sequences (MARS) were originally developed to improve the visualisation of periprosthetic bone and soft-tissue structures in patients following joint arthroplasty [14]. MARS reduces the size and intensity of susceptibility artifacts from magnetic field distortion, promising to allow otherwise non-diagnostic studies due to the metal artifact to be able to yield key diagnostic information [9–12,14]. In arthroplasty patients, MARS has been valued in the assessment of soft tissues despite the metallic implant [14]. Manufacturers have developed their own proprietary MAR sequences. For example, Siemens has developed WARP and slice encoding for metal artifact correction (SEMAC) sequences; likewise, GE has developed VAT and MAVRIC, with other manufacturers offering similar sequences. These generally use principles of MARS, including multidirectional view angle tilting to reduce in-plane distortion and a two-dimensional fast spin-echo sequence, which are phase encoded in the third dimension and reduce through-section distortion by using complex reconstruction algorithms [11].

As the number of ACL injuries, reconstructions, and ruptures continues to increase, a validated method to reliably assess graft integrity becomes increasingly necessary [3]. The purpose of our study is to determine whether MRI with MARS is superior to conventional knee MRI sequences in the visualisation and diagnostic accuracy for ACL graft rupture in knees that have previously undergone ACLR. We propose that the addition of metal reduction sequencing will reduce artifact distortion of the ACL graft; thus, improving the diagnostic accuracy of identifying a graft rupture as well as tunnel visualisation in the setting of ACLR.

2. Methods

Approval for this project from our institutional Research Ethics Board (Pro00086602).

2.1. Cohort

A computer search of all knee MRI examinations was conducted to identify patients who underwent scans with MARS following a secondary injury to their ACL reconstructed knee. MARS was recommended to be added to these patients after the senior author’s clinical examination and the presence of metallic implants. Post ACLR patients who underwent an MRI evaluation of their ACLR between November 2018 to April 2019 had additional MARS sequencing to conventional MRI sequences. We identified 18 patients and 19 knees (male, 6; female, 12; age, 33 ± 11.9 years) (see Table 1).

2.2. Imaging

All patients were examined with a 1.5T Siemens Avanto imaging system (Siemens AG, Munich). The MRI protocol included five routine triplanar spin-echo MR sequences plus two additional MAR sequences: WARP for view angle tilting, and SEMAC. For this study, we compared 3 sequences: the routinely acquired sagittal proton density fat saturated (PDFS) (repetition time TR/echo time TE = 2350/38 ms; slice thickness ST 3 mm; field of view FOV = 170 × 170 mm; matrix size 448 × 448;

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Patient demographics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male 6 Females 12</td>
</tr>
<tr>
<td>Age</td>
<td>15–19 5 20–34 5 35–44 4 45–54 4</td>
</tr>
<tr>
<td>Tibial Fixation</td>
<td>Metal suspension (e.g. cortical buttons, staples, and cross pins) 8 Metal interference screw 10 Bioabsorbable interference screw 1</td>
</tr>
<tr>
<td>Femoral Fixation</td>
<td>Metal suspension 13 Metal interference screw 3 Bioabsorbable interference screw 2 Over the top ACL 1</td>
</tr>
</tbody>
</table>

Abbreviation: ACL, anterior cruciate ligament
bandwidth BW = 140 Hz/voxel); PDFS with WARP artifact reduction (same quoted parameters as PDFS); and PDFS with slice encoding for metal artifact reduction artifact reduction (TR/TE = 3000/29, ST 4 mm, FOV = 170 × 170 mm, matrix 256 × 256; BW = 975). PDFS was chosen as the comparative sequence as it is the standard ACL MRI sequence provided at our institution. PDFS has been used as a sequence that visualises the ACL well, and is widely used in the assessment of ACL tears [15].

2.3. Image analysis

An MRI assessment was completed by six raters (three orthopaedic surgeons with fellowship training in sports medicine, two fellowship-trained musculoskeletal radiologists, and one medical student). All patient identifiers were removed from the scans, and raters were unaware of the patient's diagnosis and clinical history. However, because the visual differences between the sequences are obvious, raters could not be kept unaware to the MRI sequence (PDFS, WARP, and SEMAC). Scans from patients were analysed to compare the efficacy between MRI sequences, and images were assessed qualitatively and semi-quantitatively using a Likert scale. The visualisation of the ACL graft, PCL, medial and lateral menisci, tibial and femoral tunnel margins, and articular cartilage was rated on a scale of 1–5 (1 = cannot visualise, 2 = very blurry or indistinct, 3 = moderately blurry or indistinct, 4 = mildly blurry or indistinct, and 5 = excellent visualisation). Confidence in the diagnosis of the ACL rupture and meniscus tear was rated on a scale from –5 to 5 (–5 = definitely ruptured with high confidence, 0 = equivocal, and 5 = definitely intact with high confidence). Cyclops lesions were also assessed on a similar scale from –5 to 5 (–5 = definitely present with high confidence, 0 = equivocal, and 5 = definitely not present with high confidence). Lastly, an assessment of X-rays was performed by each reader to determine the ACL graft fixation type.

2.4. Statistical analysis

Inter-rater reliability was calculated with an intra-class correlation coefficient (two-way random, single score) using SPSS. Using the mean scores of all 6 raters, differences in the visualisation and diagnostic confidence scores derived from PDFS, WARP, and SEMAC were evaluated using the non-parametric Friedman test for multiple repeated comparisons. Conover post-hoc analysis was performed to determine which of the sequences were significantly different from one another.

3. Results

3.1. Relative visualisation of structures

The ACL graft was “mildly blurry or indistinct” with all sequences, with mean scores of 3.79/5, 3.96/5, and 3.97/5 for PDFS, WARP, and SEMAC, respectively. The native PCL had “excellent visualisation” with all sequences, with mean scores of 4.75/5, 4.81/5, and 4.63/5 for PDFS, WARP, and SEMAC, respectively (see Table 2).

3.2. Cruciate ligaments

There was no statistically significant difference in the visualisation of the ACL graft between the 3 sequences (p = 0.193) (Table 2). A further analysis was performed in 58% of cases (11/19 knees) where ACL graft visualisation was rated “moderately blurry, indistinct, or worse”. In these cases, a statistically significant increase in visualisation with SEMAC was found compared to PDFS (p = 0.041) (Table 2A) Fig. 3. Native PCL visualisation scores were best with PDFS and worst with SEMAC (p = 0.006) (Table 2).

3.3. Cartilage

The visualisation of the femoral and tibial articular cartilage was statistically and significantly worse using the SEMAC and WARP sequences than PDFS (p < 0.00001) (Table 2) Fig. 1.

3.4. Bony tunnels

The femoral and tibial tunnels were better visualised from the WARP and SEMAC sequences than the PDFS sequence. This was statistically significant (p = 0.001 femoral tunnel; p = 0.002 tibial tunnel) (Table 2) Fig. 1.

### Table 2

A comparison of the visualisation scores of the structures within the knee between PDFS, WARP, and SEMAC MRI using a semi-quantitative scale (1 = cannot visualise, 2 = very blurry or indistinct, 3 = moderately blurry or indistinct, 4 = mildly blurry or indistinct, and 5 = excellent visualisation), using 6-reader mean data.

<table>
<thead>
<tr>
<th></th>
<th>PDFS Median (IQR)</th>
<th>WARP Median (IQR)</th>
<th>SEMAC Median (IQR)</th>
<th>Friedman test (repeated multiple comparisons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL graft</td>
<td>3.83 (2.87–4.67)</td>
<td>4.33 (3.25–4.79)</td>
<td>4.17 (3.83–4.29)</td>
<td>p = 0.193</td>
</tr>
<tr>
<td>PCL</td>
<td>5.00 (4.50–5.00)</td>
<td>5.00 (4.71–5.00)</td>
<td>4.67 (4.50–4.83)</td>
<td>p = 0.006</td>
</tr>
<tr>
<td>Femoral</td>
<td>4.33 (2.96–4.68)</td>
<td>4.67 (3.58–4.83)</td>
<td>4.67 (4.00–4.79)</td>
<td>p = 0.001</td>
</tr>
<tr>
<td>Tibial</td>
<td>3.83 (3.25–4.46)</td>
<td>4.50 (3.42–4.79)</td>
<td>4.33 (4.04–4.67)</td>
<td>p = 0.002</td>
</tr>
<tr>
<td>Medial</td>
<td>4.83 (4.71–5.00)</td>
<td>4.67 (4.43–4.83)</td>
<td>3.67 (3.50–3.83)</td>
<td>p &lt; 0.00001</td>
</tr>
<tr>
<td>Lateral</td>
<td>4.50 (4.20–4.83)</td>
<td>4.67 (4.37–4.83)</td>
<td>3.37 (3.67–3.67)</td>
<td>p &lt; 0.00001</td>
</tr>
</tbody>
</table>

Conover post-hoc analysis used.
Abbreviations: ACL, anterior cruciate ligament; MRI, magnetic resonance imaging; PCL, posterior cruciate ligament.

### Table 2A

A comparison of visualisation scores in the cases with moderately blurry or indistinct ACL graft visualisation on the PDFS sequence (n = 11).

<table>
<thead>
<tr>
<th></th>
<th>6-Reader Mean Visualisation Scores</th>
<th>Friedman test (repeated multiple comparisons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDFS Median (IQR)</td>
<td>WARP Median (IQR)</td>
<td>SEMAC Median (IQR)</td>
</tr>
<tr>
<td>ACL graft</td>
<td>3.0 (2.5–4.3)</td>
<td>3.5 (2.8–4.5)</td>
</tr>
</tbody>
</table>

Conover post-hoc analysis used.
Abbreviations: ACL, anterior cruciate ligament
SEMAC significantly different from PDFS.
3.5. Menisci

Median visualisation scores for the medial meniscus were best with PDFS and worst with SEMAC \( (p < 0.00001) \). Lateral meniscus visualisation was best with WARP and worst with SEMAC \( (p < 0.00001) \) \(^\text{a}\) (Table 2) Fig. 2.

\(^\text{a}\)Note that the slight difference in the slice between SEMAC compared to PDFS and WARP is due to the difference in slice thickness – SEMAC uses thicker 4 mm slices versus 3 mm slices for the other sequences. ACL, anterior cruciate ligament

3.6. Diagnostic confidence

There was no statistically significant difference in the diagnostic confidence for the ACL rupture or cyclops lesion between the three sequences \(^\text{a}\) \((\text{Table 3})\). In the subset of cases with a moderately blurry or indistinct ACL visualisation score by at least one rater, diagnostic confidence scores for ACL graft rupture significantly improved with the use of the SEMAC sequence compared to both WARP and PDFS \( (p = 0.041) \) \(^\text{a}\) (Table 3A).

Diagostic confidence scores were found to be statistically and significantly lower for the lateral meniscus tear using SEMAC than for PDFS or WARP \( (p = 0.036) \), SEMAC and WARP sequences both produced poorer diagnostic confidence scores for the medial meniscus tear than PDFS \( (p < 0.0001) \) \(^\text{a}\) (Table 3).

3.7. Diagnostic accuracy

There was no statistically significant difference in the inter-observer reliability between each sequence. There was a trend of slightly higher inter-observer reliability for all structures on PDFS sequences compared to WARP, which was also slightly higher than SEMAC; however, these did not reach statistical significance. For PDFS, the inter-observer reliability was moderate for the ACL graft \((\text{ICC} 0.713)\) and medial meniscus \((\text{ICC} 0.630)\) and poor for the lateral meniscus \((\text{ICC} 0.439)\) \(^\text{a}\) (Table 4). The inter-observer reliability for WARP was moderate for the ACL graft \((\text{ICC} 0.661)\) and medial meniscus \((\text{ICC} 0.579)\) and poor for the lateral meniscus \((\text{ICC} 0.392)\). The inter-observer reliability for SEMAC was moderate for the ACL \((\text{ICC} 0.627)\) and medial meniscus \((\text{ICC} 0.593)\) and poor for the lateral meniscus \((\text{ICC} 0.374)\) \(^\text{a}\) (Table 4).

3.8. Scan time

The WARP sequence increased the scan time by 2.84 ± 0.69 min, while SEMAC added 2.95 ± 0.40 min to the standard knee MRI scan time at our institution.

\(^\text{a}\)Note that the slight difference in the slice between SEMAC compared to PDFS and WARP is due to the difference in slice thickness – SEMAC uses thicker 4 mm slices versus 3 mm slices for the other sequences. ACL, anterior cruciate ligament
Post-surgical MRI provides an assessment of graft integration, femoral and tibial tunnel positioning as well as other intra-articular injuries. The current literature supports our findings that metal suppression is beneficial in the assessment of patients who have undergone prior ACLR [14]. With the use of metal fixation devices, susceptibility artifacts make tunnel visualisation as well as graft incorporation difficult, especially, in higher field strength such as a 3.0 Tesla MR scanner [10]. Van Dyck et al. stated that the presence of the metallic implant in the tibia usually necessitates the use of MARS and that the reconstructed ACL is difficult to assess on MRI [12]. Others have suggested that metal implants only show metal artifacts and insufficient fat saturation right next to the implants and that visualisation of the ACL graft and the rest of the knee joint may be evaluated sufficiently [17,18]. We clearly demonstrate benefit in adding MARS to post ACLR MRI in the evaluation of ACL graft integrity.

McCauley et al. described using MR arthrography (MRA) in the evaluation of ACL grafts. With MRA, there was 100% sensitivity and 100% specificity in diagnosing a graft tear and there was a perfect agreement between MRA interpretations and surgical findings for the presence of the ACL tear; however, they did not compare their results to conventional MRI [19]. Vande Berg et al. described using CT arthrography for assessing the postoperative knee and determined that there is agreement between MRA interpretations and surgical findings for the presence of the ACL tear; however, they did not compare their results to conventional MRI [19]. Vande Berg et al. described using CT arthrography for assessing the postoperative knee and determined that there is agreement between MRA interpretations and surgical findings for the presence of the ACL tear; however, they did not compare their results to conventional MRI [19].

There is a paucity of literature regarding soft tissue knee imaging using MARS (see Fig. 3). This is the first study to evaluate the utility of MRI with MARS in the assessment of ACL grafts. The current literature demonstrates poor sensitivity (32–50%) and good specificity (90–100%) in evaluating for ACL graft rupture with MRI [13]. The primary outcome of this study was to identify whether graft integrity would be more confidently reported using MARS sequences (WARP or SEMAC) than conventional PDFS MRI. It is important to note that we only used these sequences on patients with clinically significant injury and in whom graft integrity was determined to be equivocal on clinical examination. We found that SEMAC significantly improved the diagnostic confidence for the ACL graft rupture versus conventional PDFS imaging, notably in the cases where the ACL was felt to be moderately blurry or indistinct on the PDFS sequence Fig. 3. A secondary finding was that both WARP and SEMAC significantly improved the visualisation of the femoral and tibial tunnels. This greatly helps in surgical planning and aids the clinician in deciding whether a multi-stage or single-stage revision procedure is needed [17,25]. The addition of a SEMAC sequence is superior to conventional MRI sequences in assessing the previous tunnels, and would be of benefit for pre-operative planning, potentially removing the need for some patients to undergo a CT scan to assess for tunnel widening and positioning. This is of a significant benefit in maintaining the as low as reasonably achievable radiation exposure in young patients and adding no additional risk to patients [26]. Furthermore, WARP and SEMAC each added under 3 min of added scanning. Adding one of these sequences to selected post-ACLR knee MRI would generally have minimal or no effect on total scanner patient throughput, while providing valuable additional diagnostic information. However, there seems to be little diagnostic benefit from adding both WARP and SEMAC sequences to the same scan. Therefore, we propose the following clinical approach (Fig. 4).

**Table 3**

A comparison of **diagnostic confidence scores** between PDFS, WARP, and SEMAC MRI sequences using the absolute value of 6-rater mean scores.

<table>
<thead>
<tr>
<th></th>
<th>PDFS Median (IQR)</th>
<th>WARP Median (IQR)</th>
<th>SEMAC Median (IQR)</th>
<th>Friedman test (repeated multiple comparisons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL graft rupture</td>
<td>3.83 (2.42-4.33)</td>
<td>3.83 (2.42-4.59)</td>
<td>4.00 (3.17-4.00)</td>
<td>p = 0.065*</td>
</tr>
<tr>
<td>Cyclops Lesion</td>
<td>3.50 (3.00-4.13)</td>
<td>3.83 (3.17-4.29)</td>
<td>3.67 (3.33-4.47)</td>
<td>p = 0.244</td>
</tr>
<tr>
<td>Lateral Meniscus</td>
<td>4.33 (3.83-4.50)</td>
<td>4.17 (3.71-4.46)</td>
<td>3.00 (2.38-3.50)</td>
<td>p = 0.036*</td>
</tr>
<tr>
<td>Medial Meniscus</td>
<td>4.00 (3.67-4.67)</td>
<td>3.83 (3.25-4.33)</td>
<td>3.50 (2.67-4.04)</td>
<td>p &lt; 0.000*</td>
</tr>
</tbody>
</table>

Conover post-hoc analysis used.

*SEMAC sig. different from PDFS and WARP.

ACL, anterior cruciate ligament; MRI, magnetic resonance imaging

**Table 3A**

A comparison of **diagnostic confidence scores** in the cases with moderately blurry or indistinct ACL graft visualisation on the PDFS sequence (n = 11).

<table>
<thead>
<tr>
<th></th>
<th>PDFS Median (IQR)</th>
<th>WARP Median (IQR)</th>
<th>SEMAC Median (IQR)</th>
<th>Friedman test (Repeated multiple comparisons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL graft rupture</td>
<td>2.67 (2.08-3.96)</td>
<td>2.67 (2.21-4.17)</td>
<td>3.17 (3.04-4.17)</td>
<td>p = 0.044*</td>
</tr>
</tbody>
</table>

*SEMAC sig. different from PDFS and WARP.

ACL, anterior cruciate ligament

**Table 4**

An inter-observer correlation coefficient of the diagnostic confidence of the ACL graft rupture and medial and lateral meniscus tear between PDFS, WARP, and SEMAC MRI.

<table>
<thead>
<tr>
<th></th>
<th>PDFS</th>
<th>WARP</th>
<th>SEMAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL graft rupture</td>
<td>0.713</td>
<td>0.661</td>
<td>0.627</td>
</tr>
<tr>
<td>Medial meniscus tear</td>
<td>0.630</td>
<td>0.579</td>
<td>0.593</td>
</tr>
<tr>
<td>Lateral meniscus tear</td>
<td>0.439</td>
<td>0.392</td>
<td>0.374</td>
</tr>
</tbody>
</table>

ACL, anterior cruciate ligament; MRI, magnetic resonance imaging

4. **Discussion**

There is a paucity of literature regarding soft tissue knee imaging using MARS (see Fig. 3). This is the first study to evaluate the utility of MRI with MARS in the assessment of ACL grafts. The current literature demonstrates poor sensitivity (32–50%) and good specificity (90–100%) in evaluating for ACL graft rupture with MRI [13]. The primary outcome of this study was to identify whether graft integrity would be more confidently reported using MARS sequences (WARP or SEMAC) than conventional PDFS MRI. It is important to note that we only used these sequences on patients with clinically significant injury and in whom graft integrity was determined to be equivocal on clinical examination. We found that SEMAC significantly improved the diagnostic confidence for the ACL graft rupture versus conventional PDFS imaging, notably in the cases where the ACL was felt to be moderately blurry or indistinct on the PDFS sequence Fig. 3. A secondary finding was that both WARP and SEMAC significantly improved the visualisation of the femoral and tibial tunnels. This greatly helps in surgical planning and aids the clinician in deciding whether a multi-stage or single-stage revision procedure is needed [17,25]. The addition of a SEMAC sequence is superior to conventional MRI sequences in assessing the previous tunnels, and would be of benefit for pre-operative planning, potentially removing the need for some patients to undergo a CT scan to assess for tunnel widening and positioning. This is of a significant benefit in maintaining the as low as reasonably achievable radiation exposure in young patients and adding no additional risk to patients [26]. Furthermore, WARP and SEMAC each added under 3 min of added scanning. Adding one of these sequences to selected post-ACLR knee MRI would generally have minimal or no effect on total scanner patient throughput, while providing valuable additional diagnostic information. However, there seems to be little diagnostic benefit from adding both WARP and SEMAC sequences to the same scan. Therefore, we propose the following clinical approach (Fig. 4).
integrity is not well visualised with routine knee MRI sequencing and that there is a clear role for MARS in these cases.

The MRI at our institution is a 1.5T coil, and despite the smaller coil, we achieved good image quality. Artifacts from metal hardware are more extensive with a higher magnetic field due to basic physics principles. The study by Jungmann et al. showed that a less powerful magnet actually gives excellent metal suppression and therefore improved image quality [17]. This demonstrates good generalisability for this technique including the use in less developed countries or in countries with a publicly funded healthcare system, such as Canada. Whether the MARS MRI is also of benefit in 3T MRI is an area for further study.

4.1. Strengths and limitations

To our knowledge, this is the first study evaluating the use of metal suppression MRI protocols specifically to assess ACL graft integrity. Our semiquantitative grading systems were straightforward to apply with high and consistent inter-observer reliability for the diagnosis of graft tears amongst 6 raters. We acknowledge that there is no validated rating scale in the assessment of the ACL graft in a post-injury setting. There is no validated rating scale for assessing the ACL or ACL graft integrity on MRI, and therefore, we developed our scale to evaluate graft integrity and other intra-articular structures, semi-quantitatively. Furthermore, all

Fig. 3. A comparison of 3 consecutive slices on the MRI of the ACL graft seen on PDFS (A, B, C) and SEMAC (D, E, F). The ACL graft was reported as a complete rupture on PDFS and reported to be intact on SEMAC. This highlights visually our quantitative finding that the diagnostic confidence of ACL graft rupture was increased with metal suppression sequences.

*Note that the slight difference in the slice between SEMAC compared to PDFS and WARP is due to the difference in slice thickness – SEMAC uses thicker 4 mm slices versus 3 mm slices for the other sequences. ACL, anterior cruciate ligament; MRI, magnetic resonance imaging

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To our knowledge, this is the first study evaluating the use of metal suppression MRI protocols specifically to assess ACL graft integrity. Our semiquantitative grading systems were straightforward to apply with high and consistent inter-observer reliability for the diagnosis of graft tears amongst 6 raters. We acknowledge that there is no validated rating scale in the assessment of the ACL graft in a post-injury setting. There is no validated rating scale for assessing the ACL or ACL graft integrity on MRI, and therefore, we developed our scale to evaluate graft integrity and other intra-articular structures, semi-quantitatively. Furthermore, all

Fig. 4. The algorithm for ordering WARP or SEMAC metal suppression sequences in the evaluation of ACLR knee. ACLR, anterior cruciate ligament reconstruction
MRI scans were performed at a single institution using Siemens scanners, limiting our ability to draw conclusions about the generalisability of results to other manufacturers, although this did allow for consistent image quality for evaluation. Lastly, we only assessed whether a graft was torn or not, without assessing completeness of the tear. Other studies that have assessed the utility of MRI post ACLR have commented on the ability to differentiate between partial and complete graft tears, which we did not do in this study. At our institution, partial graft tears would rarely proceed to a revision surgery, therefore we felt that the key distinction relevant to clinical management was to diagnose a complete graft tear. In this study design, we wanted to see if there was any benefit to MARS and therefore decided against routine arthroscopy in all patients due to invasiveness and potential risks. Therefore, we were not able to verify the MRI findings with arthroscopy in all patients; however, all complete graft tears were verified at the time of the revision surgery. We also acknowledge the relatively small cohort size of 18 patients. Our sample size calculation determined a minimum sample of 10 scans to achieve a statistical significance between the different sequences, and we were able to study a larger sample size than what was determined in our sample size calculation.

We believe a prospective study evaluating graft integrity using MARS compared to arthroscopy may provide additional information on the true utility of these sequences in evaluating the injured post-ACLR reconstructed knee. Future research with a larger patient cohort would allow a clearer distinction between the relative benefits of each MAR sequence, as well as possible stratification based on the graft type and graft fixation.

5. Conclusion

We found that compared to conventional MRI imaging, sequences dedicated to metal artifact reduction significantly improved the assessment of ACL graft integrity and associated bony tunnels, which may provide clinicians important information for diagnosis and surgical planning with no risk of ionising radiation to the patient and only minutes of the increased scan time. When the key clinical question is ACL graft integrity, we recommend adding a SEMAC sequence to the routine knee MRI scan protocol.

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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