Article published online: 2025-02-25

Original Article

Reliability of Slice-Encoding for Metal Artifact Correction (SEMAC) MRI to Identify Prosthesis Loosening in Patients with Painful Knee Arthroplasty: A Prospective, Single-Center, Surgical Validation Study

Tsuneari Takahashi[1,2] Siddharth Thaker[3] Giovanni Lettieri[1,4] Anthony Redmond[1,4,5] Michael R. Backhouse[1,6] Martin Stone[4,5] Philip J. O'Connor[4,5] Hemant Pandit[1,4,5]

[1] Leeds Institute of Rheumatic and Musculoskeletal Medicine, University of Leeds, Leeds, United Kingdom
[2] Department of Orthopaedic Surgery, Jichi Medical University, Shimotsuke, Tochigi, Japan
[3] Department of Radiology, Leicester Royal Infirmary, University Hospitals of Leicester NHS Trust, Leicester, United Kingdom
[4] Chapel Allerton Hospital, Leeds Teaching Hospital NHS Trust, Leeds, United Kingdom
[5] The NIHR Leeds Biomedical Research Centre, Leeds, United Kingdom
[6] Warwick Clinical Trials Unit, Warwick Medical School, University of Warwick, Coventry, United Kingdom

Address for correspondence Siddharth Thaker, MBBS, MD, FRCR, Department of Radiology, Leicester Royal Infirmary, University Hospitals of Leicester NHS Trust, Leicester LE1 5WW, United Kingdom (e-mail: Siddharthnthaker@gmail.com).

Indian J Radiol Imaging

Abstract

Objectives To validate reliability of slice-encoding for metal artifact correction (SEMAC) sequences in identifying prosthesis loosening in patients with painful knee arthroplasties (KAs) by comparing SEMAC-magnetic resonance imaging (MRI) findings to surgical outcomes—the gold standard.

Materials and Methods We prospectively followed 44 painful KA patients with possible aseptic prosthesis loosening at our tertiary care institution from 2011 to 2017. Potential cases of infective loosening were excluded making ours a selective study population. We acquired conventional and SEMAC-MRI images for all patients on 1.5-T MRI scanner. Two consultants scored MRI findings for complications such as osteolysis and bone marrow edema systematically. Scoring variations were settled by consensus. We used the Mann–Whitney *U* test and Wilcoxon signed-rank test for quantitative analysis and Spearman's rank-order correlation for correlation analysis of SEMAC findings and surgical outcomes, and followed the Outcome Measurements in Rheumatology filter methodology to assess the ability of SEMAC-MRI to detect prosthetic loosening.

Results Eleven patients needed revision surgery—seven had prosthesis loosening and four had retained native compartment osteoarthritis. Thirty-three were treated

Keywords
- knee arthroplasty
- MRI
- artifact reduction
- SEMAC
- revision surgery

DOI https://doi.org/10.1055/s-0045-1802970.
ISSN 0971-3026.

Thieme Medical and Scientific Publishers Pvt. Ltd., A-12, 2nd Floor, Sector 2, Noida-201301 UP, India

conservatively, of which 17 had spontaneous pain resolution and 8 had extra-articular causes—referred pain from hip (1 patient) and lumbar (7 patients) degeneration. Eight patients had adequate pain control without prosthesis loosening on follow-up. T1W-SEMAC identified surgically proven prosthesis loosening in all cases and short tau inversion recovery (STIR)-SEMAC diagnosed bone marrow edema (BME) in all our true positive cases. Sensitivity, specificity, positive predictive value, and negative predictive value of SEMAC-MRI for component loosening compared with gold standard were 100, 97.0, 88.9, and 100% in T1W-SEMAC, 75.0, 45.5, 25.0, and 88.2% in STIR-SEMAC, and 75.0, 93.9, 75.0, and 93.9% in proton density-weighted-SEMAC.

Conclusion SEMAC-MRI can accurately detect surgically verifiable prosthesis loosening and differentiate nonspecific BME from prosthesis loosening.

Introduction

Around 100,000 knee arthroplasties (KAs) are performed in the United Kingdom annually with objectives of adequate pain control and improved joint function. Unfortunately, up to 20% of KA patients have suboptimal outcome.[1] Aseptic prosthesis loosening, a frequent cause of painful KA, may show normal radiographs and blood tests[2,3] making its diagnosis challenging. Its diagnosis is vital to guide appropriate management in symptomatic patients and monitoring at-risk patients.[4]

Magnetic resonance imaging (MRI) is an established imaging technique for postoperative knee evaluation.[5,6] It can readily identify causative factors of prosthesis failure such as synovitis, infections, periprosthetic osteolysis, periprosthetic fractures, arthrofibrosis, and extensor mechanism injury.[7,8] Its utility is limited by magnetic susceptibility artifacts. They include implant-related magnetic field inhomogeneities producing geometric distortion, signal voids, and signal "pileup" artifacts[9–11] and inhomogenous spectral fat suppression due to failure of maintaining homogenous field strength.[4] Short tau inversion recovery (STIR) sequence, although affected by artifacts,[5] could still diagnose periarticular fluid collections or periprosthetic osteolysis.

Researchers have tested various MR parameter adjustments to image prostheses, which include fast spin echo, higher bandwidth, intermediate echo time, larger matrix, higher excitations, and thinner slices. Higher bandwidth was found to be the most effective parameter.[12]

New acquisition protocols have been developed to further rectify prosthesis-related in-plane and through-plane artifacts. For instance, view angle tilting (VAT) or metal artifact reduction sequence reduces only in-plane distortions,[13,14] whereas multiacquisition variable resonance image combination (MAVRIC) and slice-encoding for metal artifact correction (SEMAC) sequences rectify both.

MAVRIC uses several fast spin echo images at different off-resonance frequencies generating a combined image.[15–17] SEMAC uses two-dimensional slice selective excitations followed by phase-encoding each slice in additional *Z*-axis forming a composite image[18,19] providing better contrast resolution.[20] Conventional STIR can detect only 50% of the abnormal findings compared with STIR-SEMAC[21] making SEMAC superior to detect complications.[22]

After searching multiple scientific databases including PubMed, Embase, and Medline, we concluded that there are numerous studies that confirm superiority of SEMAC-MRI over conventional sequences but no studies have yet validated preoperative SEMAC-MRI findings intraoperatively during the revision surgery. Our prime objective was to assess the ability of SEMAC-MRI to detect prosthesis loosening using surgical findings and outcomes as our gold standard. We have used the Outcome Measurements in Rheumatology (OMERACT filter) methodology for validating our SEMAC-MRI findings.

Materials and Methods

Patient Selection

After receiving the regional health research authority permission for the study, we obtained an institutional ethics committee approval. All patients provided written consent prior to their participation in the study. From orthopaedic follow-up clinic, we prospectively recruited 44 patients with knee pain following various KA performed at our tertiary care institution between January 2011 and October 2017. Among them, 30 had total KA (TKA), 11 had unicompartmental KA, and 3 had patellofemoral joint arthroplasty. Each of 44 patients received a thorough orthopaedic assessment to diagnose the cause of painful KA. Clinical assessment included detailed history, clinical examination of the affected and the contralateral knee, as well as both hips and spine. Additionally, all patients had had a standardized hematological workup including inflammatory markers, including white cell count, erythrocyte sedimentation rate, and C-reactive protein. Prior to the study cohort formation, we excluded individuals with painful KA following trauma and the patients in whom infection was suspected clinically. Hence, our study population was by design selective for patients with possible periprosthetic osteolysis and aseptic loosening. The following additional exclusion criteria were used: pregnancy, contraindication to MRI, and inability to use dedicated knee coil (SEMAC

Table 1 MRI parameters

Sequence	T1W-SEMAC coronal	STIR-SEMAC sagittal	PDW-SEMAC sagittal
TR (ms)	512	3340	3000
TE (ms)	8.3	62	8.9
TI (ms)	–	160	–
Slice thickness (mm)	3.5	3.5	3.5
Voxel size	0.6 0.4 3.5 mm	0.9 0.5 2009;3.5 mm	0.6 0.4 3.5
Slices	25	26	26
ETL	–	49	50
FOV (mm)	200	200	200
Base resolution	448	384	448
NSA	1	2	1
Bandwidth (Hz/Px)	507	592	507
Acquisition time (min)	4:53	5:32	2:35

Abbreviations: ETL, echo train length; FOV, field of view; Hz/Px, hertz/pixel; MRI, magnetic resonance imaging; NSA, number of signal average; PDW, proton density-weighted; SEMAC, slice-encoding for metal artifact correction; STIR, short tau inversion recovery; TE, echo time; TI, time to invert; TR, repetition time.

sequences acquisition in a flex-coil is significantly different than that in a dedicated knee coil).

The mean clinical presentation time from the initial arthroplasty was 5.2 years with a range of 1 to 14 years. The mean age of patients at MRI was 67.5 years (standard deviation 9.0, range 49–88 years) (►**Table 1**). We performed radiographs for symptomatic knees prior to MRI in all patients. No patient was lost to follow-up. The revision surgery was performed within an average of 18 months after the MRI (range 0.5–53 months) and was used as the gold standard against which SEMAC-MRI findings were assessed.

Image Acquisition

We imaged all patients with 1.5T MRI scanner (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany). All patients were scanned in supine position. Using dedicated eight receiver channels knee coil, we acquired high bandwidth conventional proton density-weighted (PDW) axial, T1W coronal, STIR sagittal, PDW sagittal, and PDW coronal sequences. SEMAC-MRI sequences included T1 coronal, PD, and STIR sagittal, parameters of which can be found in ►**Table 1**.

Image Interpretation

Two consultants (25 and 15 years of professional experience) assessed optimized conventional and SEMAC-MRI images for periprosthetic signal changes (►**Fig. 1**) including high signal on STIR images, low signal on T1, and iso- to high signal on PDW images in periprosthetic areas, fluid collection in soft tissue, joint effusion, and synovitis.

Quantitative Analysis

The components were consensus-scored for diagnostic quality on a five-point scale: (0) definitely nondiagnostic, (1) probably nondiagnostic, (2) possibly diagnostic, (3) probably diagnostic, and (4) definitely diagnostic. Abnormalities were assessed on MRI using a four-point scale: (0) none, (1) mild, (2) moderate, and (3) severe.

We categorized periprosthetic MR signal abnormalities into periprosthetic osteolysis with or without fluid infiltration and periprosthetic bone marrow edema (BME). An area of focal low intensity in T1W and/or isointensity on PDW that displayed an absence of T1W fatty marrow signal was termed osteolysis, and associated STIR high signal in the area of T1W low signal intensity was termed periprosthetic fluid infiltration. Diffuse high intensity on STIR around the prosthesis with preserved T1 fatty marrow signal was defined as BME (►**Fig. 2**). Osteolysis and/or abnormal intensity area around the prosthesis/bone interface in each sequence were recorded by prosthesis zone in a standardized fashion by an experienced musculoskeletal radiologist. The morphology of periprosthetic zones varies

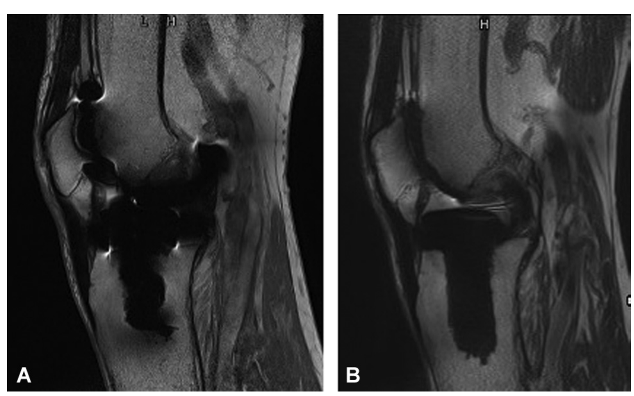

Fig. 1 An 88-year-old man with total knee arthroplasty of the left knee. (**A**) Magnetic resonance imaging (MRI) artifacts induced by the prosthesis on high bandwidth sagittal proton density-weighted (PDW) images completely hampering visualization of periprosthetic areas and (**B**) PDW images using slice-encoding for metal artifact correction (PDW-SEMAC) acquisition demonstrating remarkable reduction in metallic artifacts making evaluation of periprosthetic bone easier.

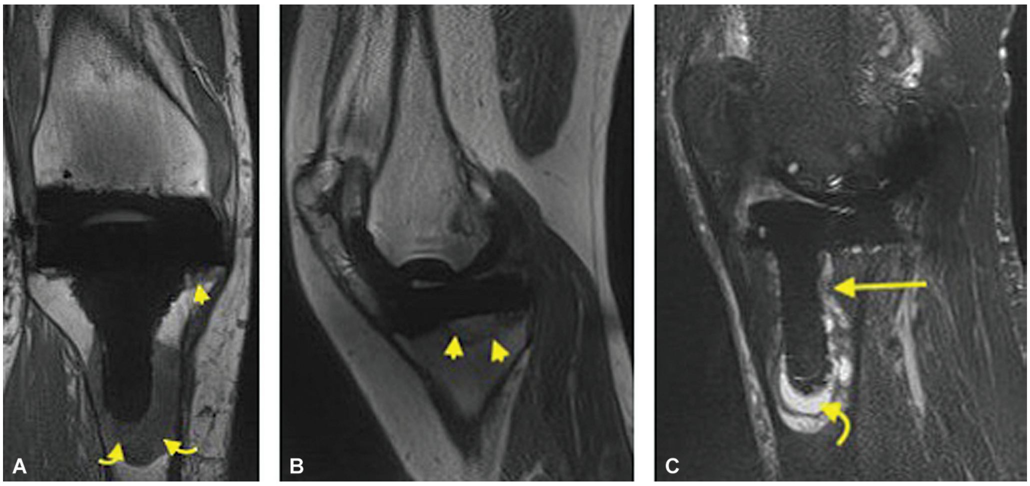

Fig. 2 (**A**) A 71-year-old man with bicompartmental total knee arthroplasty with patellar preservation of the right knee. T1-weighted coronal image using slice-encoding for metal artifact correction (T1W-SEMAC) acquisition showing irregular hypointense signal at the bone–prosthesis junction underneath the tibial plate (yellow arrowhead) and adjacent to the tibial keel (yellow curved arrows) with absence of cortical trabeculations consistent with substantial periprosthetic osteolysis and proton density-weighted sagittal image acquired using slice-encoding for metal artifact correction (PDW-SEMAC) protocol showing hyperintense signal underneath the tibial plate (yellow arrow) at the bone–prosthesis junction with absent trabeculae suggestive of periprosthetic osteolysis. (**B**) A 64-year-old woman with bicompartmental total knee arthroplasty of the right knee. T1-weighted coronal image using slice-encoding for metal artifact correction (T1W-SEMAC) acquisition showing irregular hypointense signal at the bone–prosthesis junction underneath the tibial plate and adjacent to the tibial peg (yellow arrowheads) with absence of cortical trabeculations consistent with substantial periprosthetic osteolysis and proton density-weighted sagittal image acquired using slice-encoding for metal artifact correction (PDW-SEMAC) protocol showing hyperintense signal underneath the tibial plate (yellow arrowheads) at the bone–prosthesis junction with absent trabeculae suggestive of periprosthetic osteolysis. (**C**) A 71-year-old man with total knee arthroplasty with patellar preservation of the right knee. Short tau inversion recovery (STIR) sagittal image using slice-encoding for metal artifact correction (STIR-SEMAC) protocol showing higher signal but not following fluid signal intensity just posterior to the tibial peg (zone 3, yellow arrow) and a few bony trabeculae passing through increased signal suggesting bone marrow edema (BME) and further fluid signal at the tip of the tibial peg with absent bony trabeculae through it (zone 2, yellow curved arrow) in keeping with periprosthetic osteolysis.

considerably in different arthroplasties—TKA, unicompartmental KA, and patellofemoral joint arthroplasty (►**Figs. 3**–**5**).

Reference Standard

Prosthesis loosening or revision surgery due to loosening during the follow-up periods was considered as a primary endpoint. Operating surgeons used a standardized pro forma to record surgical findings. The pro forma included the following questions: whether the implant was loose or not? If loose, which anatomical area—femur, tibia, or patella—were involved? Was there any associated osteolysis or not? If present, which part of the implant was affected by the osteolysis? And did the surgical findings correlate with the MRI findings or not?

We used the statistical methods as described below to determine the relationship between the primary endpoint

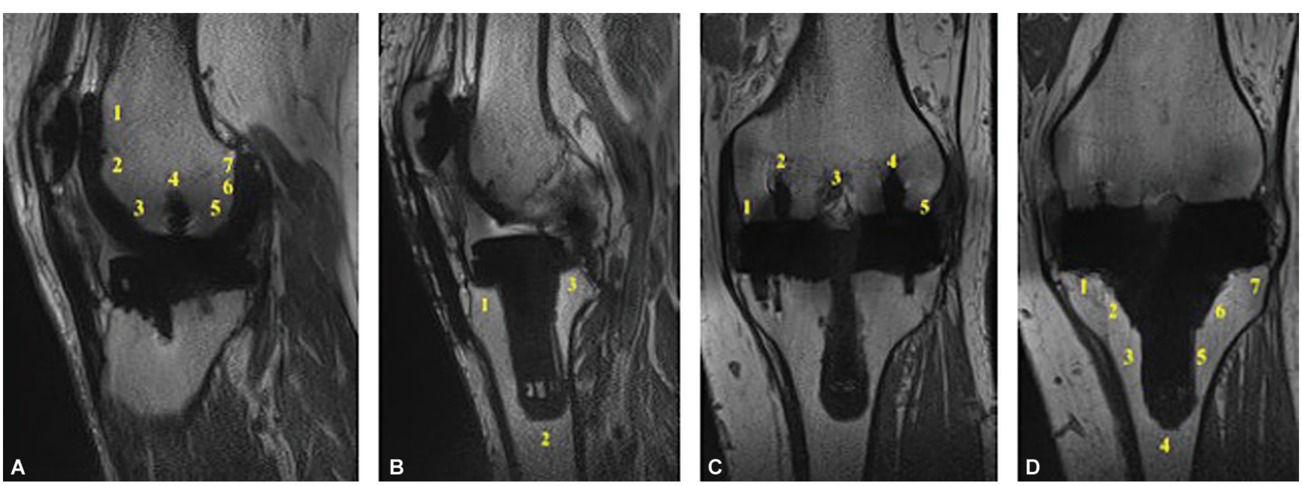

Fig. 3 (**A**) A 67-year-old man with total knee arthroplasty of the left knee. Proton density-weighted sagittal image with slice-encoding for metal artifact correction (PDW-SEMAC) acquisition demonstrating predefined periprosthetic zones around the femoral component (**A**) and around the tibial component (**B**). T1-weighted coronal image with slice-encoding for metal artifact correction (T1W-SEMAC) showing periprosthetic zones around the femoral component (**C**) and the tibial component (**D**) readers used to score findings of osteolysis or bone marrow edema (BME).

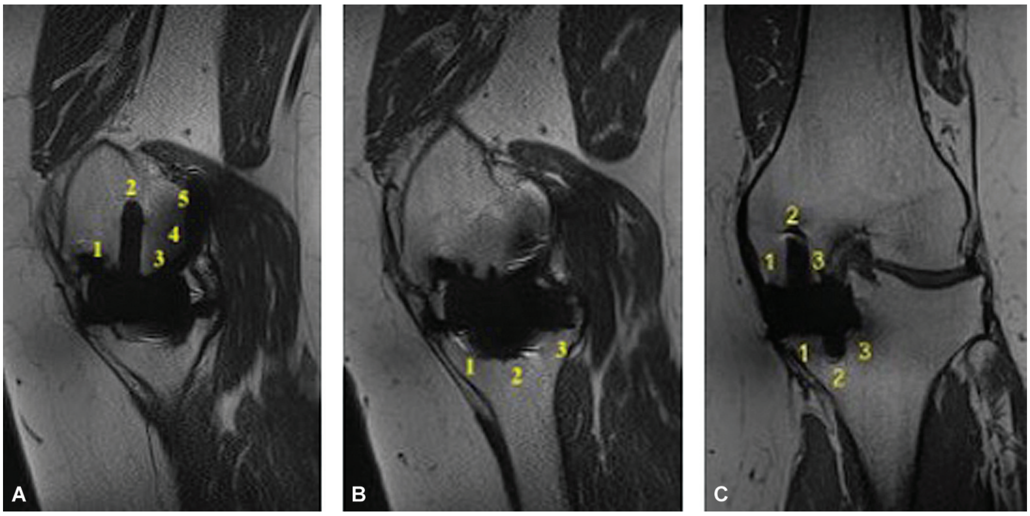

Fig. 4 (**A**) A 66-year-old man with unicompartmental knee arthroplasty of the left knee. Proton density-weighted sagittal image with slice-encoding for metal artifact correction (PDW-SEMAC) acquisition demonstrating predefined periprosthetic zones around the femoral component (**A**) and around the tibial component (**B**). T1-weighted coronal image with slice-encoding for metal artifact correction (T1W-SEMAC) showing periprosthetic zones around the femoral and tibial component (**C**) readers used to score findings of osteolysis or bone marrow edema (BME).

(prosthesis loosening on surgery) and prosthesis loosening on SEMAC-MRI.

Statistical Analysis

We used statistical software package (SPSS for windows, version 21, Chicago, Illinois, United States) for statistical analysis. We employed the Mann–Whitney *U* test and Wilcoxon signed-rank test for quantitative analysis using nonparametric point scales and Spearman's rank-order correlation for correlation analysis. A *p*-value of < 0.05 was considered as significant. Additionally, we have calculated sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of all T1W, PDW, and STIR SEMAC sequences to predict prosthesis loosening or the need for revision surgery.

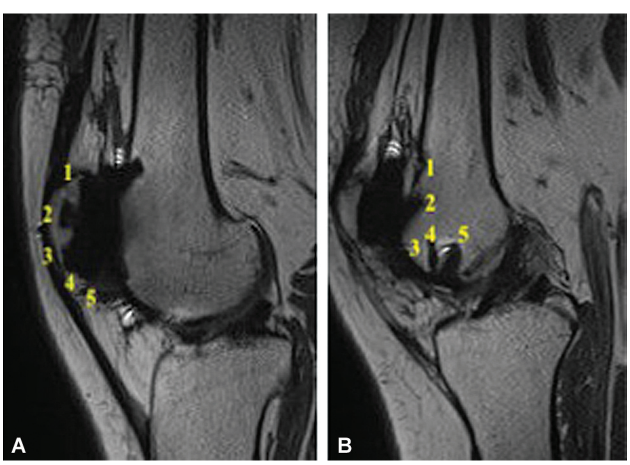

Fig. 5 (**A**) A 52-year-old woman with patellofemoral joint arthroplasty of the right knee. Proton density-weighted sagittal image with slice-encoding for metal artifact correction (PDW-SEMAC) acquisition demonstrating predefined periprosthetic zones around the patella (**A**) and around the femoral trochlea (**B**) readers used for scoring.

Results

Visualization of Bone–Cement/Bone–Prosthesis Interface with and without SEMAC

Diagnostic quality between bone and cement/prosthesis is evident by significantly higher visualization scores while using SEMAC acquisition than conventional MRI for each zone of femur and tibia. Conversely, there were no significant differences between SEMAC and conventional MRI in any zone of patella (►**Table 2**).

Abnormal Findings in Cases without and with Prosthesis Loosening

We observed significant statistical differences in abnormal findings on SEMAC-MRI between cases with and without prosthesis loosening, most readily seen in sagittal zone 1 and coronal zone 1 to 7 in the tibia, as well as the femur and patella on sagittal planes (►**Table 3**).

We have identified 11 patients who needed revision surgery following painful KA. Among them, seven cases—all of whom have had TKA—have prosthesis loosening on MRI, confirmed during the revision surgery. Of remaining four patients, three patients with patellofemoral joint arthroplasty and one patient with unicompartmental KA did not have loose prosthesis and have undergone revision to the TKA for progressive arthritis in the retained native compartments, that is, progressive lateral femorotibial and patellofemoral compartment involvement.

Thirty-three cases were treated conservatively. Seventeen patients had recovered from pain on follow-up, whereas the rest had experienced variable degrees of pain. Out of 17 patients who recovered from pain, 8 individuals had extra-articular attributable causes such as hip osteoarthritis (OA) (2 cases) and lumbar stenosis (6 cases). The remaining 16 patients continued experiencing pain on follow-up. Among

Table 2 Visualization of interface between bone and cement/prosthesis (on sagittal and coronal images)

		STIR CONV	STIR SEMAC	*p*-Value	PD CONV	PD SEMAC	*p*-Value			T1 CONV	T1 SEMAC	*p*-Value
Femur	Zone.1	0.16 (0.80)	1.8 (0.89)	< 0.001	0.92 (1.2)	3.2 (0.58)	< 0.001	**Tibia**	Zone.1	1.5 (1.5)	3.2 (0.77)	< 0.001
(sag)	Zone.2	0.16 (0.80)	1.8 (0.94)	< 0.001	0.92 (1.2)	3.2 (0.52)	< 0.001	**(Cor)**	Zone.2	1.5 (1.5)	3.3 (0.78)	< 0.001
	Zone.3	0.16 (0.80)	1.7 (0.92)	< 0.001	0.92 (1.1)	3.2 (0.52)	< 0.001		Zone.3	1.4 (1.4)	3.4 (0.59)	< 0.001
	Zone.4	0.16 (0.80)	1.6 (0.99)	< 0.001	0.56 (0.87)	3.1 (0.53)	< 0.001		Zone.4	1.9 (1.4)	3.3 (1.1)	0.0021
	Zone.5	0.16 (0.80)	1.8 (0.89)	< 0.001	0.68 (0.99)	3.2 (0.55)	< 0.001		Zone.5	1.9 (1.4)	3.4 (0.62)	0.0013
	Zone.6	0.22 (0.94)	2.1 (0.70)	< 0.001	0.72 (0.96)	3.4 (0.50)	< 0.001		Zone.6	1.9 (1.4)	3.3 (0.70)	0.0020
	Zone.7	0.22 (0.94)	2.2 (0.73)	< 0.001	0.78 (1.0)	3.4 (0.50)	< 0.001		Zone.7	1.9 (1.4)	3.3 (0.70)	0.0020
Tibia	Zone.1	0.38 (0.92)	2.2 (1.3)	< 0.001	1.3 (1.3)	3.1 (0.74)	< 0.001	**Femur**	Zone.1	0.58 (0.88)	3.1 (0.89)	< 0.001
(sag)	Zone.2	0.54 (1.2)	2.0 (1.4)	< 0.001	1.3 (1.3)	3.1 (0.78)	< 0.001	**(Cor)**	Zone.2	0.58 (0.88)	3.1 (0.79)	< 0.001
	Zone.3	0.38 (0.92)	2.2 (1.3)	< 0.001	1.3 (1.3)	3.1 (0.74)	< 0.001		Zone.3	0.58 (0.88)	3.1 (0.79)	< 0.001
Patella	Zone.1	1.0 (1.2)	1.9 (0.69)	0.077	2.6 (1.1)	3.0 (0.93)	0.201		Zone.4	0.78 (0.94)	3.0 (0.82)	< 0.001
(sag)	Zone.2	1.0 (1.2)	1.9 (0.69)	0.077	2.6 (1.1)	3.0 (0.93)	0.201		Zone.5	0.78 (0.94)	3.0 (0.82)	<0.001
	Zone.3	0.63 (1.1)	1.9 (0.69)	0.047	2.5 (1.1)	3.0 (0.93)	0.104					
	Zone.4	0.63 (1.1)	1.6 (0.98)	0.125	2.5 (1.1)	2.9 (0.99)	0.201					
	Zone.5	0.63 (1.1)	1.7 (0.76)	0.056	2.5 (1.1)	2.9 (0.99)	0.201					

Abbreviations: Cor, coronal; PD, proton density; PD CONV, conventional PD-weighted; Sag, sagittal; SEMAC, slice-encoding for metal artifact correction; STIR, short tau inversion recovery; STIR CONV, conventional STIR; T1 CONV, conventional T1-weighted.
Note: Data are expressed as mean (standard deviation).

Table 3 Abnormal finding between cases with and without prosthesis loosening (on sagittal and coronal images)

		Stable	Loosening	*p*-Value			Stable	Loosening	*p*-Value
Femur	Zone.1	0.19 (0.54)	0.43 (1.1)	> 0.05	**Femur**	Zone.1	0.09 (0.30)	0.50 (0.84)	> 0.05
(sag)	Zone.2	0.06 (0.25)	0.43 (1.1)	> 0.05	**(Cor)**	Zone.2	0.0 (0.0)	0.17 (0.41)	> 0.05
	Zone.3	0.06 (0.25)	0.43 (1.1)	> 0.05		Zone.3	0.0 (0.0)	0.17 (0.41)	> 0.05
	Zone.4	0.0 (0.0)	0.0 (0.0)	> 0.05		Zone.4	0.0 (0.0)	0.20 (0.45)	> 0.05
	Zone.5	0.0 (0.0)	0.29 (0.76)	> 0.05		Zone.5	0.11 (0.33)	0.20 (0.45)	> 0.05
	Zone.6	0.27 (0.47)	0.50 (1.2)	> 0.05	**Tibia**	Zone.1	0.17 (0.39)	1.5 (0.55)	< 0.001
	Zone.7	0.27 (0.47)	0.50 (0.84)	> 0.05	**(Cor)**	Zone.2	0.0 (0.0)	1.5 (0.55)	< 0.001
Tibia	Zone.1	0.40 (0.50)	1.1 (0.89)	0.034		Zone.3	0.08 (0.29)	1.2 (1.2)	0.0056
(sag)	Zone.2	0.43 (0.85)	1.0 (1.5)	> 0.05		Zone.4	0.0 (0.0)	1.5 (1.3)	0.0043
	Zone.3	0.53 (0.64)	1.0 (1.0)	> 0.05		Zone.5	0.0 (0.0)	1.6 (1.1)	0.0021
Patella	Zone.1	0.0 (0.0)	0.0 (0.0)	> 0.05		Zone.6	0.0 (0.0)	1.4 (0.89)	0.0451
(sag)	Zone.2	0.0 (0.0)	0.0 (0.0)	> 0.05		Zone.7	0.11 (0.33)	1.0 (0.71)	0.0097
	Zone.3	0.0 (0.0)	0.0 (0.0)	> 0.05					
	Zone.4	0.0 (0.0)	0.0 (0.0)	> 0.05					
	Zone.5	0.20 (0.44)	0.0 (0.0)	> 0.05					

Abbreviations: Cor, coronal; Sag, sagittal.
Note: Data are expressed as mean (standard deviation).

them, 8 had extra-articular causes of knee pain such as hip OA (1 case) and lumbar stenosis (7 cases). In the remaining 8 cases, the pain was adequately controlled with oral analgesics, and there was no radiological evidence of prosthesis loosening or subsidence during the follow-up period. The patients who continue to experience knee pain without identifiable intra-, peri-, and extra-articular causes on imaging were attributed to soft tissue causes such as muscle imbalance and weakness. They were treated with physiotherapy and oral analgesics. We have summarized the patient flow in ►**Fig. 6**.

T1W-SEMAC sequence has reliably depicted osteolysis and prosthesis loosening in all true positive cases ($n = 7$, medial femoral condyle and medial tibial osteolysis 1 case, medial tibial osteolysis 4 cases, and medial and lateral tibial debonding 2 cases), which were confirmed intraoperatively. There was a strong correlation between positive findings of osteolysis and surgical findings of prosthesis loosening ($r = 0.882$, $p < 0.001$). STIR-SEMAC sequence diagnosed BME when present ($n = 21$, around the femoral peg 4 cases, beneath the femoral component 5 cases, keel of tibial component 13 cases, and beneath the tibial component 7 cases).

There was also a strong correlation between the primary endpoint and positive findings of osteolysis ($r = 0.845$, $p < 0.001$) in T1W- and/or PDW-SEMAC and fluid around the prosthesis ($r = 0.758$, $p < 0.001$) in PDW-SEMAC. On the other hand, there was no significant correlation between primary endpoint and positive findings of BME in STIR-SEMAC ($r = 0.234$, $p = 0.14$) (►**Table 4**).

Sensitivity, specificity, PPV, and NPV were 100, 97.0, 88.9, and 100% in T1 SEMAC, 75.0, 45.5, 25.0, and 88.2% in STIR-SEMAC, and 75.0, 93.9, 75.0, and 93.9% in PD SEMAC, respectively (►**Table 5**).

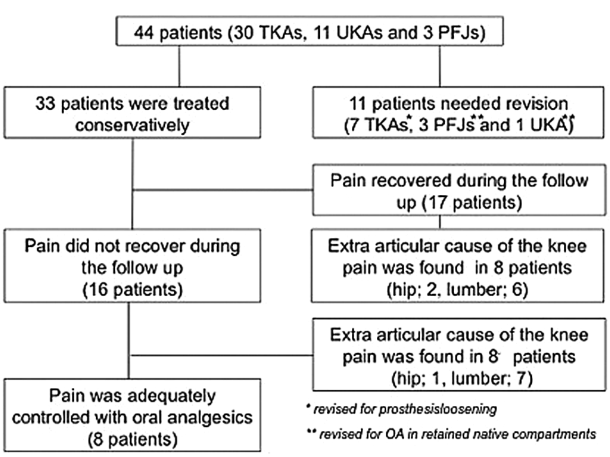

Fig. 6 Flowchart showing complete follow-up of study participants. Surgical and conservative management of all patients and outcomes on follow-up are described in detail in the article text.

Table 4 Correlation[a] between primary endpoint and positive findings in SEMAC-MRI

	r	*p*-Value
Cyst formation (focal periprosthetic abnormality)	0.845	< 0.001
Fluid collection (broad periprosthetic abnormality)	0.758	< 0.001
Bone marrow edema (increase STIR signal with preserved trabeculi)	0.234	0.14

Abbreviations: MRI, magnetic resonance imaging; SEMAC, slice-encoding for metal artifact correction; STIR, short tau inversion recovery.
[a]Comparison by use of Spearman's rank-order correlation.

Table 5 Sensitivity, specificity, PPV, and NPV of SEMAC-MRI compared with the gold standard to detect prosthesis loosening

	Sensitivity	Specificity	PPV	NPV
T1W-SEMAC	100	97.0	88.9	100
STIR-SEMAC	75.0	45.5	25.0	88.2
PDW-SEMAC	75.0	93.9	75.0	93.9

Abbreviations: MRI, magnetic resonance imaging; NPV, negative predictive value; PDW, proton density-weighted; PPV, positive predictive value; SEMAC, slice-encoding for metal artifact correction; STIR, short tau inversion recovery.

Discussion

To our knowledge, this was the first study validating SEMAC-MRI appearances of prosthesis loosening on revision surgery in patients with painful KA. The main findings of our study are: (1) T1W-SEMAC sequence was the most reliable MRI sequence to detect prosthesis loosening confirmed at the time of revision surgery, (2) SEMAC-MRI was extremely reliable in detecting tibial component loosening, and (3) bone–cement/bone–prosthesis junctions and other soft tissues around the knee following KA were significantly better visualized using SEMAC-MRI.

MRI artifacts may be intrinsic (consequent to image processing) or extrinsic (patient motion or metallic artifacts) in nature.[23] Tartaglino et al has first described metal artifact reduction sequence in 1994[24] using fast spin echo with shorter echo spacing for the postoperative spine. Similarly, in 2000, Olsen et al has proven the efficacy of metal artifact reduction sequence in patient with knee surgeries allowing better visualization of periprosthetic bone and soft-tissue structures even in patients following TKA.[9]

In 2009, Lu et al have described SEMAC-MRI for the first time.[18] SEMAC-MRI corrects metal artifacts via robust encoding of each excited slice against metal-induced field inhomogeneities. As discussed earlier, such encoding is achieved by combining a VAT acquisition with additional *z*-phase encoding, which resolves the distorted excitation profiles causing through-plane distortions while VAT nullifying in-plane inhomogeneities. SEMAC corrects through-plane distortions by summing up the resolved spins in each voxel and putting them to their actual spatial locations. It does not require additional hardware, can easily be deployed with the existing whole-body MRI systems, and provides reliable images in feasible scan times, validated using phantom and by in vivo spine and knee studies.

Multiple studies have established superiority of SEMAC-MRI over higher bandwidth conventional MRI in knee imaging following various types of arthroplasties.[19,25,26] Sutter et al have used computed tomography as a reference standard to detect periprosthetic osteolysis while proving statistically significant artifact reduction on SEMAC in patients following TKA and have suggested a need for surgical correlation for a more robust assessment of periprosthetic osteolysis and prosthesis loosening. Our study has compared SEMAC-MRI findings with surgical outcomes, establishing its reliability in detecting periprosthetic osteolysis instead of proving the superiority of SEMAC over conventional MRI. Additionally, we found similar results to those of Agten et al[19] who had proven the utility of the T1W-SEMAC sequence in identifying prosthesis loosening in all KA and STIR-SEMAC for bone marrow edema in painful unicompartmental KA influencing orthopaedic surgeons' decisions. PDW-SEMAC suffers from blurring of images, has low diagnostic yield, and potentially masks relevant meniscal lesions, making it clinically irrelevant, as found in both studies.[19] Our study contradicts these findings as about half of the cases demonstrated BME on STIR-SEMAC; there was no significant correlation between surgically confirmed loosening and positive findings of BME in STIR-SEMAC (►**Table 4**). In other words, although STIR-SEMAC detected more BME in painful unicompartmental KA, it did not translate into an increase in surgically confirmed prosthesis loosening.

Filli et al used a myriad of MAVRIC, VAT, or SEMAC combinations to image prosthesis made of different metallic materials.[14,27] They compared the degree of artifact reduction in MRI achieved with SEMAC in combination with VAT and MAVRIC for standard contrast weightings and different metallic materials such as stainless steel, titanium, cobalt-chromium-molybdenum, and oxidized zirconium. They concluded that SEMAC-VAT may be preferred for titanium and oxidized zirconium implants and medium or strong SEMAC-VAT or MAVRIC modes are necessary for significant artifact reduction for stainless steel and cobalt-chromium-molybdenum implants.[28]

Our study has strengths and limitations. We have included all patients who had SEMAC-MRI for assessing painful KA, with none lost to follow-up. We have for the first time correlated SEMAC-MRI findings with outcomes of revision surgery. Surgery is currently the gold standard for prosthesis loosening detection. All our surgeons followed a standardized pro forma to record the pathologies and this was correlated with the prerevision MRI findings. Furthermore, we measured imaging and surgical outcomes using OMERACT filters,[29] justifying construct and criterion validity of a health intervention (SEMAC-MRI) outcome against a gold standard reference (revision surgery). In terms of limitations, we have only included patients with nontraumatic, noninfective painful knees following KA. Hence, the study results cannot reflect utility of SEMAC-MRI in predicting pain or symptoms for future or in detecting early loosening in asymptomatic patients. In addition, musculoskeletal radiologists were not blinded to symptoms as only symptomatic patients were imaged. To minimize observer bias, the radiologists were blinded to plain radiographic findings. In addition, although no change in symptoms or plain radiographs have been identified, we cannot exclude subtle prosthesis loosening, if present, in patients who had no revision surgery. We continued following up all patients according to the local guidelines and none have to date needed or been listed for revision surgery. The MRI sequences used are other limitations because only T1W coronal, PDW sagittal, and STIR sagittal were included in SEMAC-MRI sequences due to longer acquisition time compared with conventional sequences. Recently described compressed sensing-SEMAC can be acquired 55% faster than conventional SEMAC and is feasible for 3-T MRI.[30] Additionally, higher bandwidth pulses used in turbo spin echo sequences combined with SEMAC by local transmit coils substantially reduces through-plane distortion artifacts at 3-T in KA.[31] Hence, further experiments are needed to determine the use of compressed sensing-SEMAC at 1.5T MRI to diagnose prosthesis loosening following TKA.

In our study, eight patients with persistent painful KA without overt prosthesis loosening on follow-up were felt likely to have intra-articular cause of ongoing pain. We could not identify any mechanical cause, such as aseptic loosening, wear, infection, or instability, on clinical or radiological examinations. It is well recognized in orthopaedics that up to 20% of patients undergoing knee replacements have persistent pain without obvious mechanical cause, and these patients, generally, do not undergo revision surgery. It is possible that these patients had subtle mechanical issues in their knee prostheses undetectable by clinical and imaging assessment.

Another potential limitation is the lack of quantification of osteolysis by the operating surgeon during revision surgery. Although we followed a standardized surgical pro forma that was filled in by the operating surgeon, we did not ask the surgeon to actually measure the osteolytic area. It is extremely challenging to measure osteolysis volumetrically during revision surgery, and it did not form a part of our study design.

Despite these limitations, ours was the first study to clarify the relationship between SEMAC-MRI findings and clinical outcomes such as prosthesis loosening in patients with painful knee following KA validated by revision surgery. T1W-SEMAC sequence identified prosthesis loosening in all the cases. We inferred a strong correlation between the primary endpoint and positive findings in T1W- and/or PDW-SEMAC. We concluded that sensitivity, specificity, PPV, and NPV were high in T1W-SEMAC, whereas specificity and NPV were high in PDW-SEMAC.

Conclusion

SEMAC-MRI can reliably diagnose prosthesis loosening in patients following KA, which can be verified on revision surgery. Further study is needed to clarify whether SEMAC-MRI can predict a temporal increase in pain and symptoms or detect early loosening in asymptomatic patients.

Authors' Contributions

T.T.: Data collection, analysis, and manuscript preparation.
S.T.: Manuscript preparation and editing, image editing, and submission.
G.L.: Data collection.
A.R.: Study supervision, data collection, and review.
M.R.B.: Study design, ethics, data collection, and analysis.
M.S.: Study supervision, review, and modification.
H.P.: Study design, surgical quality control, manuscript review, and editing.
P.O.C.: Concept, study design, data collection, manuscript editing, and submission.

Registration and Grant Number

None.

Funding

This article presents independent research supported by the National Institute for Health Research (NIHR) Leeds Biomedical Research Centre (BRC) (R&D Number: RR12/10615 and REC: 12/YH/0555).

Conflict of Interest

None declared.

Acknowledgments

The research was conducted at the National Institute for Health Research (NIHR) Leeds Biomedical Research Centre; however, it was not funded by the NIHR grant. We also thank Dr. Daniel Skrzypiec for the help received in data collection and Dr. Steve Tanners from Medical Physics for developing the MR protocol.

Prof Pandit is supported in part by the National Institute for Health and Care Research (NIHR) Leeds Biomedical Research Centre (BRC) (NIHR203331) and is a senior investigation at the NIHR. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care.

Dr. O'Connor and Professor Pandit have acted as senior authors in equal measures.

References

1 National Joint Registry for England Wales Northern Ireland and Isle of Man. Annual report. In. Hemel Hempstead, United Kingdom: National Joint Registry; 2015
2 Baker PN, van der Meulen JH, Lewsey J, Gregg PJNational Joint Registry for England and Wales Data from the National Joint Registry for England and Wales. The role of pain and function in determining patient satisfaction after total knee replacement. J Bone Joint Surg Br 2007;89(07):893–900
3 Bourne RB, Chesworth BM, Davis AM, Mahomed NN, Charron KD. Patient satisfaction after total knee arthroplasty: who is satisfied and who is not? Clin Orthop Relat Res 2010;468(01):57–63
4 Fritz J, Lurie B, Potter HG. MR imaging of knee arthroplasty implants. Radiographics 2015;35(05):1483–1501
5 Wolford ML, Palso K, Bercovitz A. Hospitalization for total hip replacement among inpatients aged 45 and over: United States, 2000-2010. NCHS Data Brief 2015;(186):1–8
6 Williams SN, Wolford ML, Bercovitz A. Hospitalization for total knee replacement among inpatients aged 45 and over: United States, 2000-2010. NCHS Data Brief 2015;(210):1–8
7 Fritz J, Lurie B, Miller TT, Potter HG. MR imaging of hip arthroplasty implants. Radiographics 2014;34(04):E106–E132

8 Plodkowski AJ, Hayter CL, Miller TT, Nguyen JT, Potter HG. Lamellated hyperintense synovitis: potential MR imaging sign of an infected knee arthroplasty. Radiology 2013;266(01):256–260
9 Olsen RV, Munk PL, Lee MJ, et al. Metal artifact reduction sequence: early clinical applications. Radiographics 2000;20(03):699–712
10 Matsuura H, Inoue T, Ogasawara K, et al. Quantitative analysis of magnetic resonance imaging susceptibility artifacts caused by neurosurgical biomaterials: comparison of 0.5, 1.5, and 3.0 Tesla magnetic fields. Neurol Med Chir (Tokyo) 2005;45(08):395–398, discussion 398–399
11 Jungmann PM, Agten CA, Pfirrmann CW, Sutter R. Advances in MRI around metal. J Magn Reson Imaging 2017;46(04):972–991
12 Kumar NM, de Cesar Netto C, Schon LC, Fritz J. Metal artifact reduction magnetic resonance imaging around arthroplasty implants: the negative effect of long echo trains on the implant-related artifact. Invest Radiol 2017;52(05):310–316
13 Cho ZH, Kim DJ, Kim YK. Total inhomogeneity correction including chemical shifts and susceptibility by view angle tilting. Med Phys 1988;15(01):7–11
14 Ai T, Padua A, Goerner F, et al. SEMAC-VAT and MSVAT-SPACE sequence strategies for metal artifact reduction in 1.5T magnetic resonance imaging. Invest Radiol 2012;47(05):267–276
15 Koch KM, Lorbiecki JE, Hinks RS, King KF. A multispectral three-dimensional acquisition technique for imaging near metal implants. Magn Reson Med 2009;61(02):381–390
16 Koch KM, King KF, Carl M, Hargreaves BA. Imaging near metal: the impact of extreme static local field gradients on frequency encoding processes. Magn Reson Med 2014;71(06):2024–2034
17 Hayter CL, Koff MF, Shah P, Koch KM, Miller TT, Potter HG. MRI after arthroplasty: comparison of MAVRIC and conventional fast spin-echo techniques. AJR Am J Roentgenol 2011;197(03):W405-11
18 Lu W, Pauly KB, Gold GE, Pauly JM, Hargreaves BA. SEMAC: slice encoding for metal artifact correction in MRI. Magn Reson Med 2009;62(01):66–76
19 Agten CA, Del Grande F, Fucentese SF, Blatter S, Pfirrmann CW, Sutter R. Unicompartmental knee arthroplasty MRI: impact of slice-encoding for metal artefact correction MRI on image quality, findings and therapy decision. Eur Radiol 2015;25(07):2184–2193
20 Chen CA, Chen W, Goodman SB, et al. New MR imaging methods for metallic implants in the knee: artifact correction and clinical impact. J Magn Reson Imaging 2011;33(05):1121–1127
21 Sutter R, Ulbrich EJ, Jellus V, Nittka M, Pfirrmann CW. Reduction of metal artifacts in patients with total hip arthroplasty with slice-encoding metal artifact correction and view-angle tilting MR imaging. Radiology 2012;265(01):204–214
22 Sneag DB, Bogner EA, Potter HG. Magnetic resonance imaging evaluation of the painful total knee arthroplasty. Semin Musculoskelet Radiol 2015;19(01):40–48
23 Pusey E, Lufkin RB, Brown RK, et al. Magnetic resonance imaging artifacts: mechanism and clinical significance. Radiographics 1986;6(05):891–911
24 Tartaglino LM, Flanders AE, Vinitski S, Friedman DP. Metallic artifacts on MR images of the postoperative spine: reduction with fast spin-echo techniques. Radiology 1994;190(02):565–569
25 Sutter R, Hodek R, Fucentese SF, Nittka M, Pfirrmann CW. Total knee arthroplasty MRI featuring slice-encoding for metal artifact correction: reduction of artifacts for STIR and proton density-weighted sequences. AJR Am J Roentgenol 2013;201(06):1315–1324
26 Jawhar A, Reichert M, Kostrzewa M, et al. Usefulness of slice encoding for metal artifact correction (SEMAC) technique for reducing metal artifacts after total knee arthroplasty. Eur J Orthop Surg Traumatol 2019;29(03):659–666
27 Koch KM, Brau AC, Chen W, et al. Imaging near metal with a MAVRIC-SEMAC hybrid. Magn Reson Med 2011;65(01):71–82
28 Filli L, Jud L, Luechinger R, et al. Material-dependent implant artifact reduction using SEMAC-VAT and MAVRIC: a prospective MRI Phantom Study. Invest Radiol 2017;52(06):381–387
29 Boers M, Beaton DE, Shea BJ, et al. OMERACT filter 2.1: elaboration of the conceptual framework for outcome measurement in health intervention studies. J Rheumatol 2019;46(08):1021–1027
30 Sonnow L, Gilson WD, Raithel E, Nittka M, Wacker F, Fritz J. Instrument visualization using conventional and compressed sensing SEMAC for interventional MRI at 3T. J Magn Reson Imaging 2017
31 Bachschmidt TJ, Sutter R, Jakob PM, Pfirrmann CW, Nittka M. Knee implant imaging at 3 Tesla using high-bandwidth radiofrequency pulses. J Magn Reson Imaging 2015;41(06):1570–1580

