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Metal Artifact Reduction MR Imaging After Arthroplasty: Advances and Clinical Applications

Zhangyan Xu[1]

[1] Department of Radiology, The First Affiliated Hospital of Chongqing Medical University, Chongqing, China

Correspondence: Zhangyan Xu, Department of Radiology, The First Affiliated Hospital of Chongqing Medical University, Chongqing, China.

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Abstract

Total joint arthroplasty was an effective treatment for end-stage joint diseases, with rapid increasement and widely applied in clinical practice. Periprosthetic joint infection remains the most severe periprosthetic complications. MRI is the preferred imaging modality for evaluating musculoskeletal infections. However, conventional MRI in post-joint arthroplasty patients was significantly hindered by severe prothesis-induced artifacts, limiting the assessment of periprosthetic structures. Metal artifact reduction imaging has been developed to mitigate metal artifacts and enhance visualization of periprosthetic tissues, improving the detection and characterization of periprosthetic complications. This review systematically examines the advancements in metal artifact reduction imaging and its clinical applications in the assessment of periprosthetic complications.

Keywords: metal artifacts reduction, MRI, joint arthroplasty, periprosthetic complication

1. Introduction

Total joint arthroplasty is the most effective therapeutic intervention for managing advanced-stage osteoarthritis, with surgical volumes increasing annually in recent decades (Hamel, Toth et al., 2008; Melvin, Karthikeyan et al., 2014). The average rate of total hip arthroplasty (THA) and total knee arthroplasty (TKA) surged by 22% and 35%, respectively, across Organization for Economic Co-operation and Development (OECD) countries from 2009 to 2019 (OECD, 2021). According to the Annual Data Report on Artificial Joints in China, the number of THA and TKA witnessed a substantial increase, rising from 221,920 to 951,986 between 2011 and 2019, representing an average annual increase of 19.96% (Feng, Zhu et al., 2020). Periprosthetic complications increased gradually with the rising number of procedures, including aseptic loosening, periprosthetic fracture, linear wear, osteolysis, and periprosthetic joint infection (PJI). Among them, PJI stands as the foremost cause of TKA revision and the third leading cause for THA revision, 33% TKA revisions were attributed to PJI from a study based on national database in China (Kamath, Ong et al., 2015; Koh, Zeng et al., 2017; Long, Xie et al., 2023). PJI represents one of the most devastating complications, with associated mortality rates ranging from 2.7% to 18% (Voigt, Mosier et al., 2015), often requiring complex and challenging treatment with a result of poor prognosis (Bassetti, Castaldo et al., 2019; Long, Xie et al., 2023).

There is no single preoperative technique that can reliably diagnose PJI. Some patients exhibited nonspecific clinical manifestations, serum markers such as the erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) have only been reported with an accuracy of 76.47% and 75.00% for diagnosing PJI (Cheng, Yang et al., 2024). In addition, up to 50% of patients with aseptic periprosthetic complications also show elevated ESR and CRP (Jacobs, Cooper et al., 2014; Plummer, Berger et al., 2016). Invasive synovial fluid analysis by joint aspiration has been reported to identify about 65% of PJI cases (Abdel Karim, Andrawis et al., 2019). Microbiological and histological analyses are often limited due to low sensitivity of synovial microbiology and the fact that samples for histology are generally not available prior to revision surgery (Bassetti, Castaldo et al., 2019; Romanò, Petrosillo et al., 2020).

Radiograph examinations play a crucial role in the follow-up of patients after joint replacement surgery. Existing imaging modalities have demonstrated limited sensitivity and accuracy in detecting PJI and were not yet to be incorporated into the PJI definition (Parvizi, Zmistowski et al., 2011; Osmon, Berbari et al., 2013; Romanò, Khawashki et al., 2019; McNally, Sousa et al., 2021). Magnetic resonance imaging (MRI) plays a vital role in the evaluation of musculoskeletal diseases, however, extensive metal artifacts around joint-prostheses often hinder the visualization of periprosthetic structures. Recent advancements in MRI metal artifact reduction techniques have reported which can minimize prosthesis-induced artifacts and distortion, improving the delineation of periprosthetic tissues (Sutter, Hodek et al., 2013; Liebl, Heilmeier et al., 2015). These developments offer new possibilities for MRI-based assessment of periprosthetic complications. This review provides an advanced analysis of MRI metal artifact reduction imaging and its clinical applications in the evaluation of periprosthetic complications.

2. MRI Metal Artifact Reduction Imaging

2.1 Optimization of Conventional Sequence Parameters

The severity of MR image distortion and metal artifacts in patients after joint arthroplasty was influenced by multiple factors, including the size, shape, material, and positioning of prosthesis, as well as the field strength of main magnetic, prosthesis orientation, bandwidth, voxel size, and slice thickness etc. Studies have demonstrated that lower field strengths, prosthesis orientation parallel to the main magnetic field, and diamagnetic materials of prosthesis result in relatively fewer metal artifacts (Ariyanayagam, Malcolm et al., 2015; Jungmann, Agten et al., 2017). Additionally, adjusting sequence parameters, such as increasing bandwidth, reducing voxel size or increasing matrix resolution, and decreasing slice thickness can effectively mitigate metal artifacts, among aforementioned strategies, increasing bandwidth was the most effective in metal artifact reduction, otherwise, these adjustments may compromise image signal-to-noise ratio and prolong scan time (Toms, Smith-Bateman et al., 2010; Jiang, He et al., 2016; Talbot & Weinberg, 2016; Feuerriegel & Sutter, 2024).

2.2 View Angle Tilting (VAT)

Significant magnetic susceptibility difference between joint-prosthesis and periprosthetic tissues was existed, which leaded to the inhomogeneities of main magnetic field and caused to shifts in resonance frequencies, finally resulting in metal artifacts and distortion in both the slice selection and frequency-encoding directions. Cho et al. (Cho, Kim et al. 1988) introduced the View Angle Tilting (VAT) technique, which applies an additional frequency-encoding gradient during signal readout. This induced a tilted readout trajectory, helping correct distortion and effectively reducing metal artifacts induced by field inhomogeneities. However, the VAT technique is constrained the duration of radiofrequency excitation, the added gradient may compromise signal-to-noise ratio and blurring of image edges. Moreover, VAT was useful in mitigating in-plane metal artifacts but has limited effectiveness in addressing through-plane distortions or signal voids (Popowski, Hiltbrand et al., 2000; Reichert, Ai et al., 2015).

2.3 Slice Encoding for Metal Artifact Correction (SEMAC)

Slice Encoding for Metal Artifact Correction (SEMAC) is an advanced spin-echo sequence that extends beyond high-bandwidth and the View Angle Tilting (VAT) technique. SEMAC introduced an additional phase-encoding gradient in the third dimension (Z-phase encoding gradient) to capture signals from off-resonance tissues and quantify the extent of image distortion. These signals are later reconstructed using a dedicated reconstruction algorithm, realigning displaced structures to their true anatomical positions, ultimately producing images with significantly reduced through-plane artifacts and geometric distortions and improved imaging quality (Talbot & Weinberg, 2016).

SEMAC has been proven to mitigate not only in-plane but also through-plane metal artifacts. Studies by Ma et al. (Ma, Zuo et al., 2018) and Jawhar et al. (Jawhar, Reichert et al., 2019) demonstrated that SEMAC outperforms conventional MRI sequences by substantially reducing metal artifacts and enhancing visualization of periprosthetic bone and soft tissue. However, the primary limitation of SEMAC is its prolonged scan time, which is directly proportional to the number of slice-encoding steps (SES). The required SES is determined by the severity of field inhomogeneity, as well as the size and shape of the prosthesis (Feuerriegel & Sutter, 2024). Research suggests that achieving clinically acceptable artifact reduction in MRI following total hip arthroplasty typically requires 11-19 SES (Lee, Lim et al., 2013; Germann, Nanz et al., 2021). The other limitations of SEMAC were increased computational load and potential signal-to-noise ratio reduction.

2.4 Multi-Acquisition Variable-Resonance Image Combination (MAVRIC)

The Multi-acquisition Variable-resonance Image Combination (MAVRIC) technique employed a three-dimensional fast spin echo acquisition with multi-spectral approach to capture signals from off-resonance protons, and is designed to reduce both in-plane and through-plane metal artifacts resulting from susceptibility differences between metallic implants and surrounding tissues.

MAVRIC excited and acquired multiple overlapping narrow frequency bands, each targeting a different resonance shift, capturing signals from tissues that would otherwise be distorted or lost. Moreover, unlike traditional two-dimensional sequences, MAVRIC uses full-volume coverage, preventing slice misregistration and signal loss in areas affected by strong susceptibility gradients. Then, each individual spectral images are combined using post-processing algorithms to generate a final image with reduced metal artifacts and improved visualization of periprosthetic bone and soft tissue (Koch, Lorbiecki et al., 2009). A study by Hayter et al. (Hayter, Koff et al., 2011) demonstrated that MAVRIC significantly reduces periprosthetic metal artifacts in patients after hip, knee, and shoulder joint arthroplasty, enhancing the visualization of periprosthetic synovium, bone, and tendons, this improvement facilitates the detection of synovitis, periprosthetic osteolysis, and tendon ruptures. Additionally, a phantom study by Filli et al. (Filli, Jud et al., 2017) reported that MAVRIC outperforms SEMAC in metal artifact reduction; however, its major limitation is a prolonged scan time. Conversely, a study by Chen A et al. (Chen, Chen et al., 2011) on post-total knee arthroplasty MRI found that both MAVRIC and SEMAC significantly reduced periprosthetic metal artifacts, with no statistically significant difference between the two techniques in artifact reduction efficacy.

2.5 Multi-Acquisition Variable-Resonance Image Combination Selective (MAVRIC-SL)

The Multi-acquisition Variable-Resonance Image Combination Selective (MAVRIC-SL) technique was an advanced hybrid MRI technique, which combined MAVRIC's spectral selection technique with SEMAC's Z-phase encoding technique. By acquiring multiple spectral images across different frequency bands and subsequently reconstructing through post-processing, achieving significantly reduced metal artifacts MRI images (Koch, Brau et al., 2011). A small-sample prospective study by Nardo et al. (Nardo, Han et al., 2015) demonstrated that MAVRIC-SL effectively reduces metal-induced artifacts and enhances visualization of periprosthetic structures in both 1.5 T and 3.0 T MRI scanners. Similarly, studies by Choi et al. (Choi, Koch et al., 2015) and Kretzschmar et al. (Kretzschmar, Nardo et al., 2015) on MRI imaging of patients after hip joint arthroplasty confirmed that, compared to conventional two dimensional spin-echo sequences, MAVRIC-SL significantly minimizes metal artifacts and geometric distortions. This technique enhances the depiction of abnormal imaging findings around prosthetic joints and improves radiologists' confidence in diagnosing prosthesis-related complications.

2.6 Propeller Technology

The Propeller technique refers to a method in which signals are acquired in parallel to fill the K-space after each radiofrequency pulse excitation. Signals from multiple excitations are collected and fill the K-space in a radial pattern with a specific angle, resulting in the oversampling of the K-space center and improving the signal in the local spatial region. Different manufacturers have various names for the Propeller technique, including PROPELLER (the proprietary name for sample k-space in a rotating fashion in GE MR system), BLADE (the proprietary name for sample k-space in a rotating fashion in Siemens MR system), and ARMS (the proprietary name for sample k-space in a rotating fashion in United Imaging Healthcare MR system). This technique was mainly used as a motion resistant MRI technique to reduce motion artifacts and improve image quality (Fair, Wang et al., 2020). Additionally, the Propeller technique can also reduce magnetic susceptibility artifacts, and it has been demonstrated to outperform conventional sequences in imaging of the skull base and nasopharyngeal region (Mavroidis, Giankou et al., 2024; Xu, Liu et al., 2024). With the increasing number of metal implants and the severe interference of metal artifacts in postoperative MR imaging, which complicates the observation of surrounding structures, researchers have applied the Propeller technique to MRI imaging of patients with metal implants. A study by Li et al. (Li, Shi et al., 2022) demonstrated that the Propeller technique could reduce metal artifacts around dental implants and improve image quality. In a study on prostate diffusion-weighted imaging (DWI) following total hip replacement, it was shown that, compared to planar echo DWI, Propeller DWI significantly reduced metal artifacts and imaging distortion, providing better visualization of prostate lesions (Czarniecki, Caglic et al., 2018).

3. Clinical Applications of Metal Artifact Reduction Imaging

Metal artifact reduction MRI overcomes the limitations of traditional MRI, significantly reducing signal pile-up, signal loss, and imaging distortion around the prosthesis, improving the visualization of periprosthetic bone and soft tissues. This facilitates the detection of periprosthetic joint complication and helps differentiate between periprosthetic infections and non-infectious complications.

3.1 The Application of Metal Artifact Reduction Techniques in Structural Imaging

Serious studies have found MR imaging features, acquiring based on metal artifact reduction imaging, are beneficial for differentiating infectious from non-infectious periprosthetic complications. Schwaiger et al.

(Schwaiger, Gassert et al., 2020) investigated the usage of metal artifact reduction MRI (VAT) for distinguishing PJI from aseptic loosening after total hip arthroplasty, the results suggested that soft tissue swelling, abnormalities in both the acetabular and femoral components, and enlarged lymph nodes were more common in patients with PJI compared to those with aseptic loosening, aiding in the differentiation and guiding clinical treatment to improve prognosis. Fritz et al. (Fritz, Meshram et al., 2022) evaluated the feasibility and diagnostic efficacy of metal artifact reduction MRI (SEMAC) in diagnosing PJI after shoulder joint arthroplasty. Their study showed statistical differences between the infection and non-infection groups in joint effusion, complex joint effusion, edematous synovitis, extra-articular fluid accumulation, enlarged lymph nodes, periprosthetic bone marrow edema, and rotator cuff muscle swelling. Among these, complex joint effusion, enlarged lymph nodes, and edematous synovitis were the most effective in diagnosing PJI, with AUC values of approximately 0.91, 0.95, and 0.94, respectively, and sensitivity >85% and specificity >90%. Gao et al. (Gao, Jin et al., 2020) explored the diagnostic efficacy of metal artifact reduction (SEMAC) MRI imaging signs-layered synovitis-in determining periprosthetic infection after total hip arthroplasty, finding high sensitivity (0.80-0.88) and specificity (0.84-0.92). Galley et al. (Galley, Sutter et al., 2020) demonstrated that metal artifact reduction (SEMAC) MRI imaging features such as periosteal reaction, joint capsule swelling, and adjacent muscle edema showed significant differences between the PJI group and control groups, helping to differentiate infectious from non-infectious complications, with accuracy rates ranging from 86% to 91%. Levack et al. (Levack, Koch et al., 2022) found that metal artifact reduction (MAVRIC) MRI images were effective in diagnosing periprosthetic infection, displaying high specificity (99.6%). Inaoka et al. (Inaoka, Kitamura et al., 2022) also reported that after joint arthroplasty, metal artifact reduction (MAVRIC-SL) MRI imaging signs, including joint capsule thickening, soft tissue fluid accumulation, soft tissue swelling, pericapsular edema, and joint effusion, were indicative factors of periprosthetic infection.

3.2 The Application of Metal Artifact Reduction Techniques in Functional Imaging

Diffusion-weighted imaging (DWI) helps assess cell membrane integrity and the movement of water molecules in local tissues, providing quantitative apparent diffusion coefficient values, which are valuable for differentiating infectious from non-infectious lesions. However, clinically used-widely DWI sequences are mostly echo-planar imaging DWI, which is highly susceptible to magnetic field inhomogeneity. In patients after joint arthroplasty, EPI DWI imaging suffered from severe metal artifacts and geometric distortions, making it difficult to visualize peri-prosthetic bone and soft tissues. Previous studies have shown that Propeller (periodically rotated overlapping parallel lines with enhanced reconstruction) techniques can reduce susceptibility artifacts and improve the visualization of peri-prosthetic structures.

Currently, the application of DWI in patients after total knee/hip/shoulder joint arthroplasty remains limited. Gao et al. (Gao, Tan et al., 2023) proposed the two-dimensional multi-spectral Propeller DWI sequence, which integrated two-dimensional multi-spectral imaging and Propeller scanning techniques with diffusion-weighted imaging. In a study of 48 patients who underwent total hip arthroplasty, aforementioned sequence was used to acquire DWI images and analyze the differences in ADC values among different types of synovitis. The results showed no statistically significant differences in ADC values among the synovitis subtypes. Research on metal artifact reduction DWI sequences in patients after joint arthroplasty remains scarce, and further investigation is needed urgently.

4. Conclusions

In summary, MRI metal artifact reduction imaging has progressively evolved, with advanced techniques significantly reducing metal artifacts around prostheses and enhancing the visualization of periprosthetic bone and soft tissues. This progress plays a crucial role in detecting and differentiating periprosthetic joint complications in clinical practice. However, current research primarily focuses on the subjective evaluation of MR imaging features acquiring from structural images, while studies on functional images such as diffusion-weighted imaging (DWI) and T_2-mapping, which can supply quantitative parameters of periprosthetic bone and soft lesions, remain limited. Further investigation is warranted to expand their clinical application.

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