RESEARCH ARTICLE

3-T MRI in Patients who Received Anterior Cervical Discectomy and Fusion Surgery with MAVRIC SL IR Sequence: A Feasibility Study

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Abstract: Objective: We aimed to investigate the feasibility of multi-acquisition with variable resonance image combination slab selectivity inversion recovery (MAVRIC SL IR) sequence on 3.0 T MRI in patients with anterior cervical discectomy and fusion (ACDF) surgery compared to bandwidth-optimized short tau inversion recovery (STIR) sequence.

Methods: Paired sagittal MR images of MAVRIC SL IR and bandwidth-optimized STIR sequences were acquired and analyzed for 21 patients after ACDF surgery with PEEK cage-plate construct. Quantitative comparisons were made on the metal artifact areas of paired mid-sagittal images. In qualitative analysis, the consistency of fat suppression and visibility of anatomic structures (bone-metal interface, surrounding soft tissues, and spinal cord) were independently assessed, based on a five-point scale by two musculoskeletal radiologists, who were blind to the images and patient details.

Results: The application of the MAVRIC SL IR sequence resulted in a significant reduction of 48% in the mean area of metal artifacts ($t = -7.141$, $p < 0.001$). Based on the comments received from both the reviewers, the MAVRIC SL IR sequence showed greater visibility of the bone-metal interface ($p < 0.001$), considerable visibility of the surrounding soft tissues ($p > 0.05$) but worse visibility of the spinal cord ($p < 0.001$), including the consistency of fat suppression ($p < 0.001$) relative to the bandwidth-optimized STIR sequence.

Conclusion: With significantly reduced metal artifacts, the MAVRIC SL IR sequence can be implemented in patients undergoing ACDF surgery with PEEK cage-plate construct for 3.0 T MRI, despite the poor visibility of the spinal cord.

Keywords: Magnetic resonance imaging, spine, multi-acquisition with variable resonance image combination slab selectivity, metal artifact, fat suppression.

1. INTRODUCTION

Anterior cervical discectomy and fusion (ACDF) is currently one of the most commonly used surgical procedures for degenerative cervical pathologies, providing the benefits of prominent therapeutic effects and minimal surgical risks [1 - 3]. The fusion procedure is routinely used to restore the height of the neural foramen and cervical lordosis by replacing the intervertebral discs with various interbody grafting. Due to the benign biomechanical properties, biocompatibility, and osseointegration, PEEK-composed cages have been widely used and demonstrated to have excellent fusion rates, lower subsidence levels, adequate reconstructive effectiveness of height of the neural foramen, and cervical lordosis [4]. For increasing the postoperative spinal stability, plates and/or screws are usually placed along with interbody cages.

For postoperative assessment, high-contrast plain radiograph and CT imaging have superior properties for the display of metal implants and bones [6], while magnetic resonance imaging (MRI) offers superior soft-tissue contrast and uses nonionizing radiation [7, 8]. However, the diagnostic efficiency of MRI has been compromised concerning its susceptibility to metal artifacts, in particular high-field magnetic scanners. Considering that the application of conventional MRI sequences for imaging metal implants remains limited, several specialized techniques for metal artifact suppression have been proposed by major MRI manufacturers in recent years, including slice-encoding for metal artifact correction (SEMAC), multi-acquisition with variable resonance image combination (MAVRIC), multi-acquisition with variable resonance image combination slab selectivity (MAVRIC SL), and multiple slab acquisition with view angle tilting.
(MSVAT) [9 - 12]. One of them, MAVRIC SL, has the potential to suppress metal artifacts on spinal implant MRI due to a slice-selectivity feature.

In addition to the reduction of metal artifacts, uniform fat suppression also plays a critical role in improving the visualization of edemas, infection, abscesses, and bleeding around metal implants [13, 14]. Previous studies have shown that the short tau inversion recovery (STIR) technique is better than the frequency-selective fat saturation technique when the static magnetic field is heterogeneous [15]. Besides, fat suppression can be achieved by a combination of MAVRIC SL with a 180° inversion pulse (i.e., MAVRIC SL inversion recovery, MAVRIC SL IR).

To our knowledge, most of the previous MAVRIC SL studies have focused on large metal implants in arthroplasty [12, 16, 17]. No studies involving small metal implants in the spines have been conducted so far. Thus, the present study aimed to investigate the feasibility of the MAVRIC SL IR sequence on 3.0 T MRI for patients who received ACDF surgery with PEEK cage-plate construct compared to the bandwidth-optimized STIR sequence.

2. MATERIALS AND METHODS

2.1. Patients

This study has been approved by the Clinical Ethics Committee of Renmin Hospital of Wuhan University. The study was conducted between June 2019 and August 2019. A total of 25 patients with degenerative cervical pathologies who underwent MRI after ACDF surgery with PEEK cage-plate construct in the department of spine surgery of our institute have been informed of the purpose of this study, and they voluntarily signed the informed consent before being enrolled. Three patients were excluded due to severe motion artifacts. For significant magnetic susceptibility artifacts caused by a metal denture, one patient was excluded. Finally, this study involved 21 patients, including 13 males and 8 females (mean age = 58.6 years, range between 43 and 74 years), with the time interval ranging from 5 days to 4 years between the MRI scans and the dates of surgery. The spinal segments for fixation comprised three segments for 8 patients, four segments for 11 patients, and five segments for 2 patients.

2.2. MR Acquisition

All MR examinations were carried out on a 3-T MR scanner (Discovery 750 w, GE Medical Systems, Milwaukee, WI, USA) with a Geometry Embracing Method (GEM) Suite 32-channel spine coil. Routine protocols were performed for a cervical spine MRI, including sagittal T2WI, T1WI, and axial T2WI. Besides, fat suppression sequences for MAVRIC SL IR and bandwidth-optimized STIR were achieved on the sagittal plane. The imaging parameters for the MAVRIC SL IR sequence were as follows: TR/TE = 4960 ms/7 ms, receiver bandwidth = ± 125 kHz, FOV = 20 cm, acquisition matrix (frequency × phase) = 288 × 192, slice thickness = 3 mm, spacing = 0.5 mm, ETL = 8, inversion time = 170 ms, number of excitations = 2, and total scan time = 2 minutes 13 seconds. For further analysis, paired images of the bandwidth-optimized STIR and MAVRIC SL IR sequences were used.

2.3. Quantitative Image Analysis

Metal artifact areas on the mid-sagittal plane of both the bandwidth-optimized STIR and MAVRIC SL IR images were sketched and measured by one musculoskeletal radiologist at the AW 4.6 workstation (GE Healthcare). Each region of interest (ROI) of the metal artifact area should specifically cover the dark regions caused by the signal void, the bright regions caused by the signal pile-up, while the surrounding regions should be manifested as geometrical distortion, as shown in Fig. (1).

2.4. Qualitative Image Analysis

Two radiologists with 15- and 17-years of diagnostic experience in musculoskeletal MRI independently evaluated and compared the consistency of fat suppression and visibility of the anatomic structures, including the bone-metal interface surrounding the soft tissues, and the spinal cord on all the images acquired by the bandwidth-optimized STIR and MAVRIC SL IR sequences in random order. In order to reduce the learning bias, the reviewers were blinded to the image and patient information as well as the scanning parameters. The consistency of fat suppression was evaluated on a five-point scale (1: the complete failure of fat suppression, 2: the partial failure of fat suppression with diagnostic confidence impaired, 3: the partial failure of fat suppression without diagnostic confidence impaired, 4: the presentation of fatty tissues in a small local area as a slightly higher signal without impairing the diagnostic confidence, 5: a completely homogeneous fat suppression). The visibility of anatomic structures was assessed on a five-point scale (1: a severe artifact with non-visualizaton of the anatomical structures, 2: a moderate artifact with visualization of moderately impaired anatomical structures, 3: a mild artifact with visualization of mildly impaired anatomical structures, 4: visible artifact but almost unaffected anatomical structures, 5: barely visible artifact).

2.5. Statistical Analysis

Statistical analysis was conducted using SPSS 17.0 software. Differences between the sketched areas of metal artifacts (quantitative data) on the bandwidth-optimized STIR and MAVRIC SL IR images were assessed using a paired Student t-test. Qualitative data were analyzed with a Wilcoxon signed-rank test, including scores of fat suppression consistency and visibility of anatomical structures, with $p < 0.05$ indicated as statistically significant. Cohen’s kappa coefficient ($\kappa$) was used in the analysis of the
MRI of ACDF with MAVRIC SL IR Sequence

Qualitative data to describe the inter-observer agreement. The level of agreement was categorized according to the following criteria [18]: poor agreement ($\kappa \leq 0$), slight agreement ($0 < \kappa \leq 0.2$), fair agreement ($0.2 < \kappa \leq 0.4$), moderate agreement ($0.4 < \kappa \leq 0.6$), substantial agreement ($0.6 < \kappa \leq 0.8$), almost perfect agreement ($0.8 < \kappa < 1.0$) and perfect agreement ($\kappa = 1.0$).

3. RESULTS

3.1. Quantitative Analysis

The average areas of the metal artifacts in the MAVRIC SL IR and bandwidth-optimized STIR images were 508 ± 225 mm$^2$ and 968 ± 456 mm$^2$, respectively. Compared to the bandwidth-optimized STIR images, the average areas of the metal artifacts in the MAVRIC SL IR images ($t = -7.141$, $p < 0.001$) were significantly reduced by 48%, as shown in Fig. (2) and (3).

3.2. Qualitative Analysis

Table 1 summarizes the scores for the visibility of the anatomical structures and the consistency of fat suppression in the comparisons between the bandwidth-optimized STIR and MAVRIC SL IR images. For both reviewers, the MAVRIC SL IR sequence provided better visibility of the bone-metal interface ($p < 0.001$) as compared with the bandwidth-optimized STIR sequence, however, similar visibility was noticed for the surrounding soft tissues ($p > 0.05$) in both the techniques. However, inferior visibility of the spinal cords ($p < 0.001$) and consistency of fat suppression was achieved by the MAVRIC SL IR sequence for both reviewers, as shown in Fig. (2).

4. DISCUSSION

As seen in the results, MAVRIC SL IR images showed considerably fewer metal artifacts and plainer bone-metal interfaces but also weakly defined spinal cords and poor fat suppression, compared to the bandwidth-optimized STIR. Furthermore, both techniques provided similar visibility to the surrounding tissues.

Three factors attributed primarily to the smaller metal artifact area and clearer bone-metal interface provided by the MAVRIC SL IR images. Firstly, a series of discrete and independent RF spectral bins with limited eccentric
Fig. (3). The box plot shows differences in the metal artifact areas between bandwidth-optimized STIR and MAVRIC SL IR sequences. Measured metal artifact areas were significantly smaller in the MAVRIC SL IR images than the bandwidth-optimized STIR images.

Table 1. Mean scores of qualitative evaluation of bandwidth-optimized STIR Images and MAVRIC SL IR Images

<table>
<thead>
<tr>
<th>Rated Feature</th>
<th>Mean Score (± SD)</th>
<th>u Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>STIR</td>
<td>MAVRIC SL IR</td>
<td>-</td>
</tr>
<tr>
<td>Visibility of bone-implant interface</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reviewer 1</td>
<td>1.33 ± 0.58</td>
<td>3.95 ± 0.38</td>
<td>-4.137</td>
</tr>
<tr>
<td>Reviewer 2</td>
<td>1.38 ± 0.59</td>
<td>4.14 ± 0.57</td>
<td>-4.109</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.475</td>
<td>0.533</td>
<td>-</td>
</tr>
<tr>
<td>Visibility of surrounding soft tissues</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reviewer 1</td>
<td>3.52 ± 0.75</td>
<td>3.48 ± 0.81</td>
<td>-0.233</td>
</tr>
<tr>
<td>Reviewer 2</td>
<td>3.76 ± 0.62</td>
<td>3.57 ± 0.81</td>
<td>-0.855</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.550</td>
<td>0.710</td>
<td>-</td>
</tr>
<tr>
<td>Visibility of spinal cord</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reviewer 1</td>
<td>4.05 ± 0.50</td>
<td>3.14 ± 0.65</td>
<td>-3.497</td>
</tr>
<tr>
<td>Reviewer 2</td>
<td>4.05 ± 0.59</td>
<td>3.24 ± 0.77</td>
<td>-2.773</td>
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<tr>
<td>( \kappa )</td>
<td>0.578</td>
<td>0.665</td>
<td>-</td>
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<tr>
<td>Consistency of fat suppression</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reviewer 1</td>
<td>4.00 ± 0.45</td>
<td>3.24 ± 0.54</td>
<td>-3.557</td>
</tr>
<tr>
<td>Reviewer 2</td>
<td>4.14 ± 0.57</td>
<td>3.43 ± 0.60</td>
<td>-3.035</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.444</td>
<td>0.650</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: degree of agreement was interpreted as follows: poor agreement (\( \kappa \leq 0 \)), slight agreement (0 < \( \kappa \leq 0.2 \)), fair agreement (0.2 < \( \kappa \leq 0.4 \)), moderate agreement (0.4 < \( \kappa \leq 0.6 \)), substantial agreement (0.6 < \( \kappa \leq 0.8 \)), almost perfect agreement (0.8 < \( \kappa < 1.0 \)) and perfect agreement (\( \kappa = 1.0 \)).


*: statistically significant difference \(( p < 0.05 )\), NS: no statistical significance.

Bandwidths are used instead of a conventional broad spectral RF pulse to excite a slab in the MAVRIC SL IR sequence, generating several independent MR sub-images with different artifacts. Subsequently, these sub-images are processed by a maximum intensity projection reconstruction algorithm, including bin overlap deblurring and sum-of-
squares combination of the spectral bins, to synthesize images with fewer artifacts [19]. The utilization of discrete spectral bins in stimulating the hydrogen protons with discrete precession frequency caused by the extremely heterogeneous static magnetic field effectively improves the excitation efficiency and accuracy of the RF pulse in the highly off-resonance conditions. Secondly, the MAVRIC SL technique uses a complementary gradient in the direction of slice-selection, which is exactly the same as the phase-encoding gradient for the in-plane spatial position of the hydrogen protons, to counteract the distorted excitation profiles of the selected slices due to the metal-induced heterogeneity of the magnetic field [10]. When the complementary gradient is used, hydrogen protons are positioned to their actual spatial locations, and the aliasing effect of the through-plane is mitigated. Thirdly, the view angle tilting (VAT) technique embedded in the MAVRIC SL sequence applies an identical complementary gradient field as the frequency encoding gradient in the slice-selecting direction simultaneously during MR signal readout with an angle of \([\tan^{-1}(Gz/Gx)]\), which tilts the readout gradient field [20]. Thus, the frequency shifts of the hydrogen protons inside the slices are compensated, leading to the alleviation of in-plane displacement. As contributed by the above factors, the metal artifact area is not only decreased but the outlines of the PEEK cage-plate construct and adjacent vertebral endplates are greatly enhanced. Therefore, a more precise assessment of vertebral fusion can be achieved. Moreover, with improved visualization of the bone-metal interface, the diagnostic accuracy regarding the position and shape of the metal implants has potentially been improved by the MAVRIC SL IR sequence. In this context, Gutierrez et al. found that the application of the MAVRIC SL technique to metal implants in several body parts (total hip replacement, knee replacement, femoral neck screw, etc.) showed better visualization of the bone-implant interface through the smaller coverage of the surrounding soft tissues as compared with conventional 2D-FSE sequences [16].

The poor visibility of the spinal cord in the MAVRIC SL IR sequence can be explained by three deterministic influencing factors and one random influencing factor. Firstly, the PD-weighted images obtained from the MAVRIC SL IR sequence with long TR and short TE mainly reflected proton densities of tissues with suppressed T2 contrast. As a result, the depiction of the spinal cord is impaired by the reduced tissue contrast (deterministic influencing factor). Secondly, the image blurring, which is originated from the following influencing factors: 1: long echo train length (ETL = 20), which leads to a more significant variation of signal strength among the echoes and results in a phase calculation error during the image reconstruction process, consequently forming blurring artifacts (deterministic influence factor), 2: the MAVRIC SL images are composited by multiple original sub-images with various characteristics of artifacts using a fuzzy mathematical algorithm, which inevitably causes blurring of the synthesized images [16] (deterministic influencing factor), 3: due to the time-consuming process of the sub-images combination and the application of the complementary gradient field in the slice-selecting direction, the acquisition time of the MAVRIC SL IR sequence is about 11 minutes. Thus, some patients are unable to control the movement during the relatively long scanning time. Moreover, the MAVRIC SL technique was incompatible with the phase oversampling method [21]. In order to prevent overlapping artifacts, the phase-encoding direction can only be adjusted to the anterior-posterior direction, i.e., the short axis of the cervical spinal implant, which probably aggravates the image blurring produced by the motion artifacts from swallowing motion and movement of the neck. However, due to the different degrees of cooperation of each patient, the blurring artifacts in different patients are variable (random influencing factor).

Nevertheless, due to the negative impact of image blurring, although the metal artifacts covering the soft tissues surrounding the prostheses on the MAVRIC SL IR images, particularly the anterior part, were smaller, MAVRIC SL IR images showed no significant improvement in the visibility of the surrounding soft tissues compared to the bandwidth-optimized STIR images. However, the blurring artifacts on the cervical spine MR images were mainly due to multiple factors related to patients (physiological swallowing movement and voluntary movement of the neck). In contrast, the MAVRIC SL technique itself had several defects [16, 17].

The uniformity of fat suppression is of great importance for T2- or PD-weighted spinal images of patients with metal implantations, in addition to the metal artifacts [15, 22]. However, the inhomogeneity of the local magnetic field caused by metal implants poses significant challenges towards fat suppression [23]. When the static magnetic field (BO) is not homogeneous, it is difficult to achieve a uniform fat suppression effect using the conventional frequency-selective fat saturation technology, which is based on the specific frequency saturation pulse [24]. Unlike conventional frequency-selective fat saturation technology as a widely used fat suppression technology in clinical practice, the STIR technique uses a 180° inversion pulse to pre-saturate the longitudinal magnetization vector of fat signal unparallel to the static magnetic field, followed by a 90° excitation pulse when it recovers and reaches the zero point as the maximum value in the negative direction to that in the positive direction. Because of the fat signal just reaching the zero point no fat signal can be received [25]. With the short T1 characteristic of the fat tissue, the STIR technique is conducive to overcome metal artifacts and achieve a better fat suppression effect for its insensitivity to the inhomogeneous static magnetic field [15, 26]. Although with identical fat suppression technique, our study showed that fat suppression in the inversion recovery (IR)-based bandwidth-optimized STIR sequences was more effective than in the IR-based MAVRIC SL sequence. Two possible causes were identified in this regard. MAVRIC SL uses multiple discrete and partially overlapping excitation Gaussian pulses to excite the entire image, while composite images have been reconstructed from all sub-images in correspondence with the excitation pulses. This improves the signal-to-noise ratio of the image but accumulates an incompletely suppressed signal for fat tissue [19]. Secondly, both the magnetization transfer and the J-coupling effects in the longer ETL of the MAVRIC SL sequence have magnified the fat signal. Fortunately, the poor fat suppression effects in the MAVRIC SL IR images were
manifested mainly in the subcutaneous fatty tissue of the nape, which usually did not affect the postoperative assessment. The fat-suppressed MAVRIC SL technique was still conducive to the visualization of metal implants and the detection of lesions. This was similar to the results of the previous study [12], which concluded that the MAVRIC SL IR images had an inferior fat suppression effect and SNR but had superior visibility of the anatomical structures in the 3.0 T MRI of patients with a symptomatic total hip replacement, as compared with the FSE-STIR sequences.

There are certain shortcomings in this research as relatively small sample size was used for the analysis. In future research, more cases should be included to determine the reliability of the statistical findings. Moreover, only the metal artifacts of the PEEK cage-plate construct were studied in the ACDF surgery, thereby the application effects of the two sequences on other forms of metal implants could not be determined. Since different imaging qualities existed in the two sequences, the comparability of the two sequences was not intuitive for the reviewers. Furthermore, our study was not focused on the detection of pathologic lesions, including edemas, infection, abscesses, and bleeding. Finally, the areas of metal artifacts were measured by only one radiologist.

CONCLUSION

A significant reduction in metal artifacts adds feasibility to the clinical application of MAVRIC SL IR sequences in the 3-T MRI of patients who had undergone anterior cervical discectomy and fusion surgery with PEEK cage-plate construct. However, visualization of the spinal cord is still limited.

LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACDF</td>
<td>Anterior cervical discectomy and fusion</td>
</tr>
<tr>
<td>MAVRIC SL IR</td>
<td>Multi-acquisition with variable resonance image combination slab selectivity inversion recovery</td>
</tr>
<tr>
<td>STIR</td>
<td>Short tau inversion recovery</td>
</tr>
<tr>
<td>PEEK</td>
<td>Polyetheretherketone</td>
</tr>
<tr>
<td>SEMAC</td>
<td>Slice-encoding for metal artifact correction</td>
</tr>
<tr>
<td>MSVAT</td>
<td>Multiple slab acquisition with view angle tilting</td>
</tr>
<tr>
<td>VAT</td>
<td>View angle tilting</td>
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<tr>
<td>ETL</td>
<td>Echo-train Length</td>
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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No animals/humans were used for studies that are basis of this research.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES

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Combinatorial Chemistry & High Throughput Screening, XXX, Vol. XX, No. XX


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