



Benefits and pitfalls of iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL) imaging in clinical application of the cervical spine MR



I.-C. Chiang^a, W.-S. Chuang^{a,b}, I.-T. Hang^a, Y.-T. Kuo^{a,c}, T.-J. Hsieh^{a,c,*}

^a Department of Medical Imaging, Kaohsiung Medical University Chung Ho Memorial Hospital, Taiwan, Republic of China

^b Department of Medical Imaging, Kaohsiung Municipal Siaogang Hospital, Kaohsiung Medical University, Kaohsiung, Taiwan, Republic of China

^c Department of Medical Imaging, Chi Mei Medical Center, Tainan, Taiwan, Republic of China

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AIM: To evaluate efficacy of T2-weighted (T2W) iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL)-fast spin echo (FSE) imaging of the cervical spine.

MATERIALS AND METHODS: The cervical spine of 100 symptomatic patients was imaged using routine magnetic resonance imaging (MRI) versus IDEAL-FSE imaging. The signal-to-noise ratios (SNRs), contrast-to-noise ratios (CNRs), and image quality were analysed. To compare the diagnostic efficiency of degenerative spondylopathy, evaluations of spondylolisthesis, retrolisthesis, disc herniation, myelopathy, disc degeneration, and bone marrow oedema were also performed.

RESULTS: IDEAL-FSE showed significantly higher SNRs and CNRs (all $p < 0.001$) than fat-suppressed (FS) T2W-FSE. Sixteen of 100 patients had cervical spine instrumentation; in those patients, IDEAL-FSE provided significantly better uniformity of fat suppression ($p < 0.001$) and fewer metallic artefacts ($p < 0.001$). For patients without instrumentation, FS T2W-FSE showed significantly better overall image quality ($p < 0.001$) and homogeneity of the cerebrospinal fluid (CSF; $p < 0.001$) with fewer motion artefacts ($p < 0.001$). IDEAL-FSE, however, provided significantly better uniformity of fat suppression ($p < 0.001$). There were no significant differences in the diagnoses of spondylolisthesis, retrolisthesis, disc herniation, or myelopathy between IDEAL and FS T2W images. The only significant differences between the IDEAL and FS T2W images were noted when diagnosing degenerative disc disease at the C2–3 and C5–6 disc levels ($p = 0.019$, $p = 0.002$, respectively) and bone marrow oedema at C3 vertebral body ($p = 0.029$).

CONCLUSION: T2W IDEAL-FSE imaging should only be considered as an additional sequence to conventional FS T2W images in patients with poor fat suppression or severe metallic artefacts.

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* Guarantor and correspondent: T.-J. Hsieh, 13F, No.392, Nanping Rd., Zuoying Dist., Kaohsiung City 81355, Taiwan, Republic of China. Tel.: +86 886 9 31786252; fax: +86 886 7 5520730.

E-mail address: tsyhjyi.hsieh@gmail.com (T.-J. Hsieh).

Introduction

Magnetic resonance imaging (MRI) is an important, non-invasive method for examination of the spine.¹ MRI of the spine can detect alterations not only in the anatomy, but also in tissue properties, which may expose the underlying pathology.^{2–4} Improvements in MRI hardware and software have contributed to improvements in spatial resolution and signal-to-noise ratio (SNR).^{1,5}

Reliable and homogeneous fat suppression on T2-weighted (W) images is necessary to improve the diagnosis of cervical spine disease as a high intensity of fat on T2W images may obscure some lesions (e.g., bone marrow oedema, myelopathic signal change, and paraspinal soft-tissue oedema)^{3,6}; however, B0 field inhomogeneities, arising from magnetic susceptibility differences at the air–tissue interfaces, make conventional fat-suppressed (FS) sequences (chemical shift–selective fat suppression [CHESS]), unreliable.^{7,8} These B0 field inhomogeneities primarily occur adjacent to the airway, lung apices, and posterior neck on MRI of the cervical spine rendering image interpretation difficult.^{6,8}

Shortening of the inversion time (TI) to create a short-TI inversion-recovery (STIR) pulse sequence is currently used to improve fat suppression^{8,9}; however, the STIR sequence has major clinical limitations including long imaging times, low SNR, and high specific absorption rates (SAR), and therefore, is not suitable for contrast-enhanced imaging. Hybrid techniques using a combination of CHESS and inversion-recovery sequences can obtain a higher SNR, but at the expense of longer pulse duration and higher SAR.⁸ Unlike STIR, hybrid techniques have B0 sensitivity, which may result in heterogeneous fat suppression. To minimise this problem, a Dixon technique is recommended.^{8,10,11}

Iterative decomposition of water and fat with echo asymmetry and least-squares estimation (IDEAL) fast spin echo (FSE), a type of three-point Dixon method, has been used clinically to improve fat suppression.^{12,13} IDEAL-FSE uses chemical shift-based water–fat separation methods by exploiting differences in the resonant frequencies of water and fat.¹⁴ In the IDEAL-FSE method, three images with small relative shifts in echo time (TE) are obtained with an iterative algorithm and a least-squares pseudoinverse operation.¹⁵ Thus, local inhomogeneities in the magnetic field can be measured directly. Therefore, IDEAL-FSE can correct the chemical shift artefact in the readout direction and provide better image quality and higher SNR during fat suppression than conventional FS sequences^{10,13,16}; however, one prominent drawback to the IDEAL method is the increase in scanning time required by the multipoint data acquisition, which may limit its widespread use.⁸

The purpose of this study was to evaluate the efficacy of T2W IDEAL-FSE imaging of the cervical spine as compared with conventional FS T2W FSE imaging, including quantitative measurements and qualitative scoring of diagnostic image quality.

Materials and methods

The protocol for this study was approved by the Institutional Review Board of our Kaohsiung Medical University Chung Ho Memorial Hospital. Written informed consent was obtained from all patients prior to their participation in the study.

Study group

A total of 100 symptomatic patients who underwent routine MRI of the cervical spine were enrolled. All 100 patients were imaged using a routine MRI protocol for the cervical spine plus the T2W IDEAL-FSE sequence. No patient was excluded from the study on the basis of age, weight, severity of neurological deficit, history of prior spine surgery, or quality of the MRI examination.

MRI protocol

All 100 patients in the study group underwent MRI of the cervical spine performed with the same 3 T MRI system (Sigma HDx; GE Healthcare, Waukesha, WI, USA) using an eight-channel spinal phased-array coil and manufacturer-supplied investigational pulse sequences. All patients received conventional MRI of the cervical spine consisting of four pulse sequences¹: sagittal frequency-selective FS T2W FSE sequence (3,050 ms repetition time [TR], 117.024 ms echo time [TE], 23 echo train length [ETL], 90° flip angle, 240×240 mm field of view, 512×512 resolution, 3 mm section thickness, imaging duration= 2 minutes 5 seconds)²; axial multiple-echo recombined gradient echo (MERGE) sequence (720 ms TR, 12.974 ms TE, ETL=4, 20° flip angle, 240×240 mm field of view, 3 mm section thickness, imaging duration= 2 minutes 11 seconds)³; sagittal spin-echo (SE) T1W images (650 ms TR, 10.144 ms TE, ETL=3, 90° flip angle, 240×240 mm field of view, 3 mm section thickness, imaging duration= 2 minutes 11 seconds)⁴; axial SE T1W images (916.668 ms TR, 13.836 ms TE, ETL=2, 90° flip angle, 240×240 mm field of view, 3 mm section thickness, imaging duration= 2 minutes 11 seconds).

After the non-enhanced conventional MRI sequences, a sagittal T2W IDEAL FSE sequence (3,400 ms TR, 98.336 ms TE, ETL=16, 90° flip angle, 240×240 mm field of view, 3 mm section thickness, imaging duration= 4 minutes 20 seconds) was performed and water images were auto-calculated by the manufacturer-supplied console. Two patients, one diagnosed with a possible infection and one diagnosed with a possible tumour, received sagittal (850 ms TR, 9.968 ms TE, ETL=3, 90° flip angle, 240×240 mm field of view, 5 mm section thickness, imaging duration=2 minutes 11 seconds) and axial post-enhanced frequency-selective FS FSE sequence (1,116.67 ms TR, 14.196 ms TE, ETL=2, 90° flip angle, 240×240 mm field of view, 3 mm section thickness, imaging duration=2 minutes 11 seconds).

Quantitative evaluations of imaging qualities

The following quantitative analyses were performed for all patients on the frequency-selective FS T2W FSE imaging and the T2W IDEAL water imaging¹: SNRs of the spinal cord, cerebrospinal fluid (CSF), and normal bone marrow, and² CNRs between the CSF and spinal cord and between the CSF and bone marrow.

To calculate these values, the signal intensities (SIs) of the spinal cord, CSF, and normal bone marrow were measured three times by placing regions of interest (ROIs) at the level of second cervical vertebra (C2) and the average of the three values were used for analysis.

The four ROIs for background noise were placed at the corners of the images that lacked any structures, and standard deviations (SDs) of the SIs obtained from these measurements were used for analysis. When the positions of the ROIs had to be moved in some cases because of abnormal hyperintensities, ROIs were selected based on the relative position to adjacent tissues.

The SNR was calculated as: $SNR = SI_{\text{tissue}}/SD$ of background noise. The CNR was calculated as: $SI_{\text{tissue 1}} - SI_{\text{tissue 2}}/SD$ of background noise. SI_{tissue} defines the SI of the corresponding tissue.

Qualitative and semi-quantitative evaluations of imaging qualities

Qualitative and semi-quantitative evaluations of frequency-selective FS T2W FSE imaging and the T2W IDEAL water imaging were reviewed by three radiologists with 14, 10, and 5 years of experience, respectively, in the interpretation of MRI of the spine. Before reviewing the images, all images were randomly assigned a new identification number (ID) and the original ID and names of the patients and the sequence descriptions were erased. These procedures were performed by a radiologist who did not review these images. The renamed images were stored on digital versatile discs (DVDs) with standard Digital Imaging and Communications in Medicine (DICOM) 3 specification. The quality of these renamed images was the same as the original uncompressed DICOM images.

All images were interpreted using standard picture archiving and communication systems (PACS) software (EBM-viewer, EBM, Taiwan) on standard PACS viewer stations (dual 5 million-pixel monitors). To prevent recall bias, the radiologists reviewed the MRI examinations at separate times that were at least 2 months apart. The image interpretations were recorded using a standardised data collection form on which the reader was prompted to select from multiple-choice lists for each characteristic.

Parameters of qualitative evaluations

All images received qualitative evaluations consisting of evaluations of overall image quality, presence of motion artefact, fat-suppression quality, and CSF homogeneity. Any metallic artefact was evaluated on those images that contained orthopaedic instrumentation, i.e., internal fixation.

The radiologists graded each patient for overall image quality and fat suppression quality using a five-point scale (1, excellent; 2, good; 3, fair; 4, poor; and 5, non-visualisation). A three-point scale (1, excellent; 2, good; and 3, poor) was used to grade CSF homogeneity. The readers also evaluated the presence of motion artefacts using a five-point scale (1, no motion artefact; 2, mild artefact with sharp margins; 3, moderate artefacts with slightly blurred margin; 4, significant artefacts with significantly blurred margin; and 5, non-visualisation).

For the patients with internal fixation, a four-point scale (0, no metallic artefact; 1, mild artefact without involving the spinal cord; 3, moderate artefacts with partially involving the spinal cord; and 4, significant artefacts with non-visualisation of the spinal cord) was used.

Parameters of semi-quantitative evaluations

For comparing the diagnostic efficiency for degenerative spondylopathy, evaluations of spondylolisthesis, retrolisthesis, disc herniation, and myelopathy, and semi-quantitative evaluations of disc degeneration and subcortical bone marrow oedema were also performed.

Spondylolisthesis was defined as an anterior displacement of an upper vertebral body >1 mm and retrolisthesis was defined as a posterior displacement of an upper vertebral body >1 mm. Disc herniation was defined as posterior bulging, protrusion, or extrusion of an intervertebral disc. Myelopathy was defined as abnormal high SI within the spinal cord.

For semi-quantitative evaluation of disc degeneration, the radiologists graded images using a five-point ordinal scale. In grade I disc degeneration, the nucleus pulposus has homogeneously high SI, clear distinction of the nucleus and the annulus, and normal height of the intervertebral disk. Grade II degeneration has the same features as grade I degeneration, with the exception that the nucleus pulposus is inhomogeneous. In grade III degeneration, the nucleus pulposus is inhomogeneous with intermediate SI and the height of the intervertebral disk is normal to slightly decreased. In grade IV degeneration, the nucleus pulposus has inhomogeneously low to intermediate SI and the height of the intervertebral disk is normal to moderately decreased (residual height >50%). In grade V degeneration, the nucleus pulposus is hypointense (black), and the height of the intervertebral disk is <50%.

For semi-quantitative evaluations of bone marrow, the radiologists graded using a three-point ordinal scale. In grade 1, the bone marrow shows no abnormal high SI. In grade 2, there is slightly high SI in bone marrow. In grade 3, significantly higher SI is noted in bone marrow.

Statistical analysis

Data were analysed by one author with 10 years' experience in statistics. All statistical analyses were performed using JMP software (version 12; SAS Institute Inc., Cary, NC, USA). Differences between T2W IDEAL and the routine FS T2W protocols were evaluated using paired t-test. A *p*-value

of <0.05 (two-tailed) was considered statistically significant. Quantitative analysis was performed for all patients by calculating the average of three measurements.

Qualitative analysis was performed for three groups, i.e., all patients, patients with metallic fixation, and patients without metallic fixation. Semi-quantitative analysis was performed only for patients with degenerative spondylopathy. The averages of the data from three raters were assessed using paired *t*-test. The kappa statistic was used to test the inter-rater reliability in the qualitative analysis.

Results

Patient demographics

For inter-sequence and interobserver analyses, 200 MRI examinations from 100 patients (49 females and 51 males) were rated by all three readers. The average age of the 100 patients was 52.3 years (range, 19–78 years). One patient had spondylodiscitis, and another had a previous tumour removed. Sixteen patients (nine females and seven males; average age, 48.9 years (range, 22–65 years) had prior metallic fixation of the cervical spine; 82 patients (40 females and 42 males; average age, 52.8 years; range, 19–78 years) had degenerative spondylopathy. These 82 patients were enrolled for semi-quantitative evaluation of their degenerative spondylopathy.

Quantitative analysis of imaging qualities

The average SNRs of spinal cord (171.65 ± 13.54), CSF (433.70 ± 32.97), and bone marrow (64.96 ± 4.23) were significantly higher using the IDEAL sequence compared

with the SNRs of the spinal cord (74.42 ± 7.34 ; $p < 0.001$), CSF (230.91 ± 22.25 ; $p < 0.001$), and bone marrow (30.50 ± 3.04 ; $p < 0.001$) using the FS T2W sequence.

The average CNRs between CSF and spinal cord (262.05 ± 19.76) and between CSF and bone marrow (368.75 ± 29.44) using the IDEAL sequence were significantly higher compared with the average CNRs between CSF and spinal cord (156.49 ± 15.02 ; $p < 0.001$) and between CSF and bone marrow (200.41 ± 19.44 ; $p < 0.001$) using the FS T2W sequence.

Qualitative analysis of imaging qualities

Table 1 presents the qualitative comparisons between the IDEAL and FS T2W sequences and the interobserver variability and reliability. For patients without metallic fixation, the FS T2W sequence showed significantly better overall quality ($p < 0.001$), better CSF homogeneity ($p < 0.001$) and fewer motion artefacts ($p < 0.001$; Fig 2) compared to the IDEAL sequence. Significant qualitative improvement in fat suppression uniformity was offered by the IDEAL sequence ($p < 0.001$; Fig 3).

For patients with metallic fixation, the difference in overall quality between the IDEAL and the FS T2W sequences was not significant ($p = 0.245$). Compared with the FS T2W sequence, the IDEAL sequence provided statistically significantly better fat-suppression uniformity ($p < 0.001$) and, overall, fewer metallic artefacts ($p < 0.001$; Fig 4). Severe metallic artefacts that affected the evaluation of the adjacent spinal cord were noted in eight cases on the FS T2W images and five cases on the IDEAL images (Fig 5). The FS T2W sequence showed significantly better CSF homogeneity ($p < 0.001$) and fewer motion artefacts ($p < 0.001$).

Table 1

Qualitative comparison between IDEAL and FS T2W sequences.

Variables	IDEAL	FSE FS	Difference of (IDEAL group - FSE FS group)									
			Overall		Reader 1		Reader 2		Reader 3		Inter-rater reliability (kappa)	
			Mean±SE	Mean±SE	Mean±SE	p-Value	Mean±SE	p-Value	Mean±SE	p-Value	Mean±SE	p-Value
All patients (n=100)												
Overall quality	1.92±0.04	1.49±0.04	0.43±0.05	<0.001	0.67±0.08	<0.001	0.33±0.10	0.001	0.30±0.07	<0.001	0.31	0.25–0.38
Motion	1.78±0.04	1.16±0.03	0.63±0.04	<0.001	0.91±0.08	<0.001	0.69±0.08	<0.001	0.27±0.06	<0.001	0.31	0.28–0.34
Fat suppression	1.06±0.02	1.59±0.03	-0.52±0.03	<0.001	-0.47±0.06	<0.001	-0.62±0.06	<0.001	-0.48±0.05	<0.001	0.29	0.28–0.30
Cerebrospinal fluid homogeneity	1.50±0.03	1.02±0.01	0.46±0.03	<0.001	0.43±0.05	<0.001	0.27±0.04	<0.001	0.72±0.05	<0.001	0.43	0.35–0.49
Patients without internal fixation (n=84)												
Overall quality	1.83±0.04	1.35±0.03	0.48±0.05	<0.001	0.79±0.08	<0.001	0.32±0.10	0.001	0.33±0.08	<0.001	0.30	0.27–0.32
Motion	1.81±0.05	1.17±0.03	0.64±0.05	<0.001	0.90±0.08	<0.001	0.73±0.09	<0.001	0.29±0.06	<0.001	0.34	0.31–0.36
Fat suppression	1.06±0.02	1.58±0.04	-0.51±0.04	<0.001	-0.46±0.07	<0.001	-0.63±0.06	<0.001	-0.44±0.06	<0.001	0.29	0.23–0.34
Cerebrospinal fluid homogeneity	1.50±0.03	1.02±0.01	0.46±0.03	<0.001	0.43±0.06	<0.001	0.27±0.05	<0.001	0.73±0.05	<0.001	0.41	0.33–0.48
Patients with internal fixation (n=16)												
Overall quality	2.40±0.15	2.21±0.17	0.19±0.16	0.245	0.07±0.27	0.81	0.38±0.39	0.347	0.13±0.15	0.432	0.43	0.29–0.68
Motion	1.63±0.11	1.08±0.04	0.56±0.10	<0.001	1.00±0.20	<0.001	0.50±0.16	0.006	0.19±0.10	0.083	0.33	0.30–0.36
Fat suppression	1.06±0.04	1.65±0.08	-0.58±0.09	<0.001	-0.47±0.17	0.014	-0.56±0.16	0.003	-0.69±0.15	<0.001	0.27	0.21–0.31
Cerebrospinal fluid homogeneity	1.48±0.07	1.02±0.02	0.46±0.08	<0.001	0.47±0.13	0.004	0.25±0.11	0.041	0.69±0.12	<0.001	0.49	0.46–0.53
Metallic artefact	1.17±0.16	1.63±0.19	-0.38±0.11	<0.001	-0.67±0.16	<0.001	-0.19±0.10	0.082	-0.50±0.16	0.006	0.48	0.42–0.60

IDEAL, iterative decomposition of water and fat with echo asymmetry and least-squares estimation; FSE, fast spin echo, FS, fat-suppressed; T2W, T2-weighted.

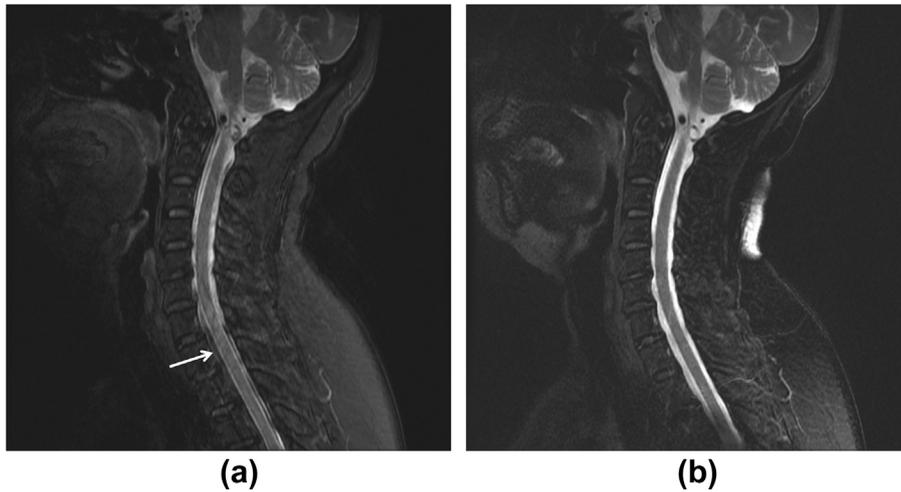


Figure 1 Sagittal MRI images of a 64-year-old woman. (a) T2W IDEAL water image shows poor homogeneity (arrow) of the CSF signal (CSF pulsation artefact), especially within the lower cervical and visible thoracic spinal canal. (b) FS T2W image shows good homogeneity of CSF signal.

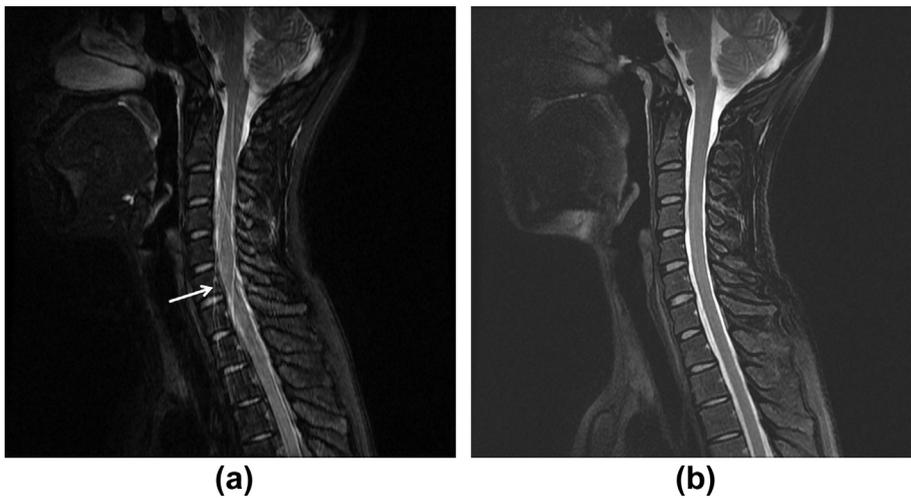


Figure 2 Sagittal MRI in a 25-year-old woman. There are more motion artefacts (arrow) in (a) T2W IDEAL water image compared with (b) FS T2W image.

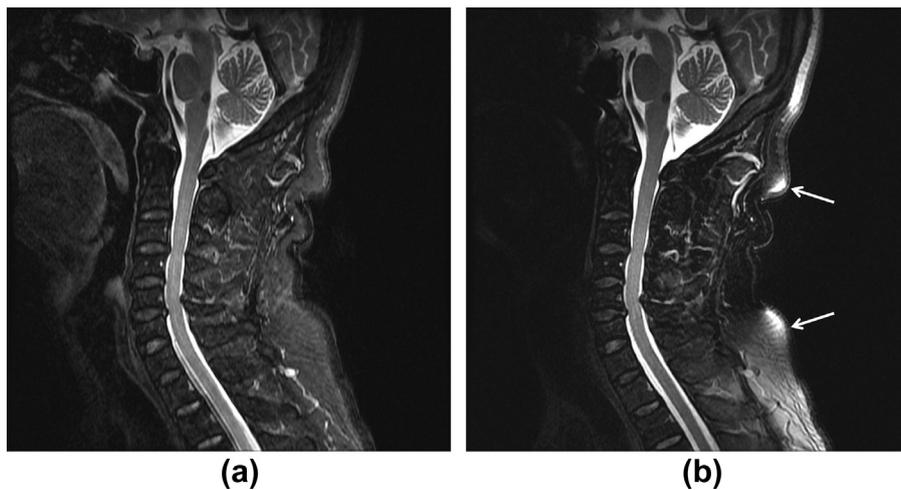


Figure 3 Sagittal MRI in 63-year-old man. (a) T2W IDEAL water image shows excellent homogeneity of fat suppression. There are some areas with poor suppression of fat signal (arrows) in (b) FS T2W image.

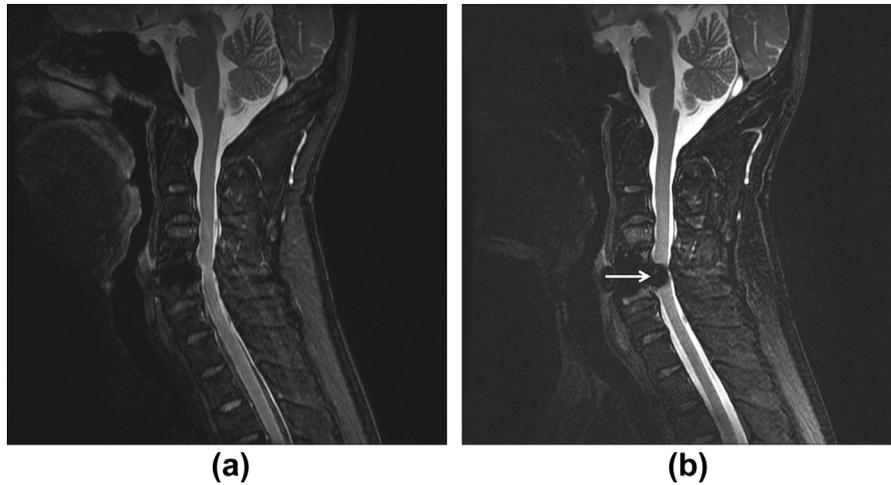


Figure 4 Sagittal MRI in a 40-year-old man with metallic cage fixation at C5–6. (a) T2W IDEAL water image shows less metallic artefact than (b) FS T2W image (arrow).

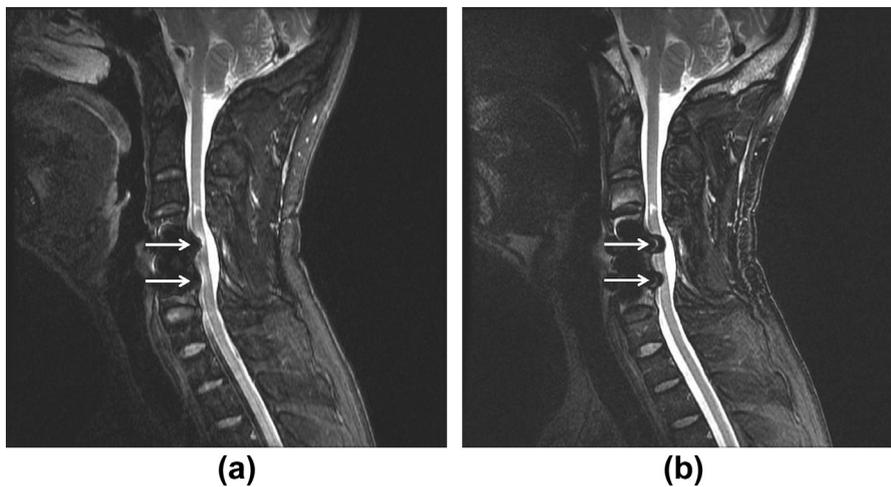


Figure 5 Sagittal MRI in a 53-year-old man with metallic cage fixations at C4–5, C5–6. (a) T2W IDEAL water image shows less metallic artefacts than (b) FS T2W image, but severe metallic artefacts (arrows), that affected the evaluation of adjacent spinal cord, are noted in both T2W IDEAL images and FS T2W images.

All three reviewers were in complete agreement with the above findings. The kappa results showed fair to substantial agreement (kappa: 0.21–0.68) among raters in the quality analysis (Table 1).

Semi-quantitative analysis of accuracy of clinical diagnosis

The semi-quantitative comparison between IDEAL and FS T2W sequences and the interobserver variability for patients with degenerative spondylopathy are presented in Table 2.

There were no significant differences in the diagnoses of spondylolisthesis, retrolisthesis, disc herniation, or myelopathy between IDEAL and FS T2W images; however, regarding intensity changes, significant differences between the IDEAL and FS T2W images were noted when diagnosing degenerative disc disease at the C2–3 and C5–6 disc levels ($p=0.019$,

$p=0.002$, respectively) and bone marrow oedema at C3 ($p=0.029$). There were no significant differences between the IDEAL and FS T2W images when diagnosing intensity changes within the other discs and vertebral bodies.

Discussion

The IDEAL-FSE sequence was found to provide better fat-suppression uniformity and fewer metallic artefacts, but more motion artefacts and worse CSF homogeneity compared with the FS T2W sequence. Similar to previous studies, the present study also showed that the IDEAL-FSE sequence provided significantly higher SNRs, and CNRs. The overall image quality of the FS T2W sequence was better than that of the IDEAL-FSE sequence in those patients without metallic fixation, but there are no significant differences in diagnostic results between the two sequences. In patients with metallic fixation, there was no significant

Table 2

Semi-quantitative comparison between IDEAL and FS T2W sequences.

Variables	IDEAL	FSE FS	Difference of (IDEAL group - FSE FS group)							
			Overall		Reader 1		Reader 2		Reader 3	
			Mean±SE	p-Value	Mean±SE	p-Value	Mean±SE	p-Value	Mean±SE	p-Value
Disk level of spondylolisthesis										
C4–5	0.02±0.01	0.02±0.01	0.00±0.01	1.000	0.00±0.00	1.000	0.00±0.00	1.000	0.00±0.00	1.000
C7–T1	0.01±0.01	0.01±0.01	0.00±0.01	0.565	0.00±0.02	1.000	0.00±0.00	1.000	0.01±0.01	0.320
Disk level of retrolisthesis										
C5–6	0.04±0.01	0.05±0.01	0.00±0.01	0.764	0.01±0.02	0.567	0.01±0.02	0.567	0.01±0.03	0.658
Disk level of degeneration										
C2–3	1.76±0.05	1.86±0.06	-0.10±0.04	0.019	0.04±0.07	0.605	0.11±0.06	0.083	0.23±0.08	0.005
C3–4	2.25±0.06	2.26±0.07	-0.01±0.05	0.879	0.23±0.07	0.003	0.13±0.11	0.230	0.10±0.09	0.270
C4–5	2.63±0.06	2.71±0.07	-0.07±0.06	0.210	0.26±0.08	0.001	0.28±0.12	0.019	0.18±0.09	0.054
C5–6	2.95±0.07	3.16±0.07	-0.21±0.07	0.002	0.26±0.08	0.003	0.51±0.11	<0.001	0.37±0.13	0.008
C6–7	2.49±0.08	2.54±0.08	-0.05±0.06	0.365	0.40±0.09	<0.001	0.23±0.10	0.021	0.32±0.09	0.001
C7–T1	1.69±0.06	1.65±0.06	0.05±0.06	0.436	0.44±0.09	<0.001	0.01±0.05	0.829	0.30±0.07	<0.001
Disk level of herniation										
C2–3	0.06±0.01	0.04±0.01	0.01±0.01	0.158	0.04±0.02	0.083	0.01±0.02	0.567	0.00±0.02	1.000
C3–4	0.58±0.03	0.57±0.03	0.02±0.02	0.372	0.05±0.04	0.208	0.01±0.02	0.658	0.00±0.03	0.658
C4–5	0.76±0.03	0.74±0.03	0.02±0.02	0.466	0.08±0.05	0.090	0.01±0.04	0.741	0.02±0.02	0.320
C5–6	0.90±0.02	0.90±0.02	0.00±0.02	0.828	0.01±0.04	0.765	0.01±0.03	0.708	0.01±0.02	0.567
C6–7	0.58±0.03	0.58±0.03	0.00±0.02	0.848	0.09±0.05	0.090	0.07±0.03	0.033	0.02±0.02	1.000
C7–T1	0.05±0.01	0.05±0.01	0.00±0.01	1.000	0.00±0.00	1.000	0.01±0.02	0.567	0.01±0.01	0.32
Vertebral level of bone marrow oedema										
C2	1.06±0.02	1.03±0.01	0.03±0.01	0.052	0.10±0.04	0.02	0.01±0.01	0.320	0.00±0.00	1.000
C3	1.10±0.02	1.07±0.02	0.04±0.02	0.029	0.14±0.04	0.002	0.01±0.01	0.320	0.04±0.02	0.083
C4	1.24±0.03	1.21±0.03	0.03±0.02	0.183	0.16±0.06	0.015	0.01±0.02	0.567	0.05±0.02	0.045
C5	1.37±0.04	1.34±0.03	0.03±0.03	0.277	0.16±0.06	0.009	0.02±0.05	0.596	0.04±0.05	0.442
C6	1.35±0.03	1.31±0.03	0.04±0.03	0.239	0.20±0.07	0.004	0.07±0.06	0.203	0.00±0.05	1.000
C7	1.13±0.05	1.14±0.03	0.01±0.03	0.640	0.05±0.06	0.397	0.09±0.04	0.052	0.00±0.03	1.000
T1	1.03±0.01	1.02±0.01	0.02±0.01	0.103	0.05±0.03	0.103	0.00±0.00	1.000	0.00±0.00	1.000
Myelopathy	0.15±0.02	0.12±0.02	0.03±0.02	0.088	0.04±0.04	0.369	0.02±0.03	0.483	0.04±0.02	0.083

IDEAL, iterative decomposition of water and fat with echo asymmetry and least-squares estimation; FSE, fast spin echo, FS, fat-suppressed; T2W, T2-weighted.

difference in overall image quality between the two sequences, although the IDEAL-FSE sequence had fewer metallic artefacts.

In the present study, the IDEAL images provided significantly higher SNRs of the spinal cord, CSF, and bone marrow and higher CNR between CSF and spinal cord and between CSF and bone marrow when compared with the FS T2W images. The present findings were similar to previous studies, which found that the IDEAL technique used all the information from source images concerning water-fat decomposition.^{12,16}

Uniformity of fat suppression on T2W images is important for the evaluation of cervical spine pathology.^{3,4,16} In the present study, although the FS T2W sequence provided good uniformity of fat suppression in most cases without metallic fixation, all three reviewers were in agreement that the IDEAL images showed better uniformity of fat suppression, not only in the patients without metallic fixation, but also in those with metallic fixation. The anatomical features of the neck are a major cause of poor uniformity of fat suppression on FS T2W sequences when imaging the cervical spine.⁶ Poor fat suppression areas usually occur near the irregular surface of the skin, the airway, or the lung apices, and may lead to a misdiagnosis.⁶ In cases of poor fat suppression on FS T2W FSE sequences, IDEAL-FSE images can still provide excellent uniformity of fat suppression, as shown in the present study.

Susceptibility artefacts due to metallic devices may not only degrade image quality and fail to provide fat suppression, but can also cause image distortion.⁶ Previous studies revealed that IDEAL images show very uniform fat saturation despite the presence of surgical screws.^{17,18} In the present study, all cases with metallic fixation had better uniformity of fat suppression and less image distortion on the IDEAL images compared with the FS T2W images; however, severe metallic artefacts on the IDEAL images were still noted in five cases and the spinal cord adjacent to the metallic devices could not be evaluated in those patients. For these cases with severe metallic artefacts on the IDEAL images, a combination of metal artefact reduction technique, such as slice-encoding for metal artefact correction, and Dixon technique may provide better fat suppression imaging quality.¹⁹

The IDEAL images had significantly more motion artefacts than the FS T2W images. The longer scan time necessary for the IDEAL sequence was an important causative factor in the increased motion artefact seen on the IDEAL images and also affected overall image quality. Thus, the IDEAL sequence may not be considered as the standard protocol for routine MRI examination of the cervical spine. Previous studies have also shown that the increase in scan time is the major disadvantage of the IDEAL sequence.⁸ To reduce motion artefact, two methods, i.e., the TurboProp and GRASE techniques, have been proposed.^{20–22} The

Turboprop utilises motion correction and the GRASE technique shortens the scan time without loss of spatial resolution. If these methods are applied clinically, an improved IDEAL image quality may be obtained during routine examination.

Homogeneity of the CSF is important for diagnosis of intradural–extramedullary lesions and external compression on the thecal sac.^{1,6} CSF homogeneity on the IDEAL images was not as good as that found on the FS T2W FSE images. The areas with poor CSF homogeneity primarily occurred at the lower cervical and upper thoracic spine. In cases of degenerative disc disease, poor CSF homogeneity made diagnosis of disc herniation difficult because the disc–CSF margin was unclear. In cases with severe loss of CSF intensity at the lower cervical and upper thoracic spine on the IDEAL images, the FS T2W images still provided good diagnostic image quality.

CSF intensity changes may have been due to CSF pulsation artefact.^{1,23} CSF pulsation artefact is a ghosting artefact that is usually associated with periodic motion, such as with CSF pulsation, cardiac motion, and respiratory motion.^{1,23} In the spinal canal, CSF pulsation artefact usually results from turbulence and time-of-flight effects associated with complex CSF flow; however, pulsation artefact is occasionally noted on conventional T2W images, although the effect is too subtle to affect the final diagnosis. In the present study, CSF pulsation artefacts were common on the IDEAL images and their influence on diagnostic accuracy was significant. It is suggested that if CSF pulsation artefacts are noted on IDEAL images, conventional T2W sequences should be obtained for definitive evaluation of the CSF region.

Although the present IDEAL images had increased motion artefacts and worse CSF inhomogeneity, there was no significant difference in the diagnosis of degenerative disc disease when compared with the FS T2W images. If these artefacts can be improved with Turboprop and GRASE techniques, the advantage of the higher SNR in the IDEAL sequence may make the IDEAL sequence more practical for use in routine cervical spine evaluations.

The present study had several limitations including the present small patient population with metallic fixation. Different metallic devices may show different metallic artefacts. A larger group of patients with metallic fixation may provide more information about the artefacts encountered during MRI evaluation in cases with different metallic devices. In addition, the radiologists were aware that all of the images were from patients who had clinical symptoms. The lack of healthy patients also may have affected the semi-quantitative evaluation of spondylolisthesis and disc herniation. In addition, most cases in the present study had degenerative spondylopathy. A larger study including patients with several diseases, such as tumours, infections, or trauma, could provide more information concerning diagnostic accuracy using the IDEAL sequence.

In conclusion, the present study showed that T2W IDEAL imaging provides high-SNR images with excellent fat suppression and less metallic artefacts when evaluating cervical spine pathology; however, due to the long scan time with relatively significant motion and CSF pulsation

artefacts, the overall imaging quality of IDEAL images is not significantly better than that of conventional FS T2W images. According to the present findings, T2W IDEAL imaging should only be considered as an additional sequence to conventional FS T2W images in patients with poor fat suppression or severe metallic artefacts and not used as a routine MRI sequence.

Conflicts of interest

The authors declare no conflict of interest.

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