

Optimal *b* value of diffusion-weighted imaging on a 3.0T magnetic resonance scanner in Crohn's disease

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Abstract

AIM: To determine the optimal *b* value of diffusion-weighted imaging for detecting active inflammation in Crohn's disease.

METHODS: Thirty-one patients clinically diagnosed with active Crohn's disease were referred for magnetic resonance examination. All patients were scanned on a 3.0T magnetic resonance scanner using the same protocol involving four different *b* values (800, 1500, 2000 and 2500 s/mm²). The diagnostic effect of diffusion-weighted imaging was evaluated and compared with endoscopic findings. The diffusion-weighted image quality of four *b* value groups was evaluated and apparent diffusion coefficient was measured for both nor-

mal and inflammatory intestinal segments.

RESULTS: The contrast-to-noise ratio and signal-to-noise ratio were not satisfied when *b* value 2000 or 2500 s/mm² was adopted (36.52 ± 14.95 vs 34.78 ± 24.83 , $P > 0.05$; 53.58 ± 23.45 vs 47.58 ± 29.67 , $P > 0.05$). The qualitative image quality was not enough to meet diagnostic requirement. No matter which *b* value was chosen, the apparent diffusion coefficient of inflammatory intestinal segments was significantly lower than that of normal intestinal segments (1.38 ± 0.28 vs 2.00 ± 0.38 , $P < 0.01$; 1.09 ± 0.20 vs 1.50 ± 0.28 , $P < 0.01$; 0.95 ± 0.19 vs 1.34 ± 0.28 , $P < 0.01$; 0.88 ± 0.14 vs 1.20 ± 0.21 , $P < 0.01$). The lesion detection rate (90.32%), diagnostic sensitivity (81.18%) and specificity (95.10%) would be appropriate when *b* value 1500 s/mm² was adopted.

CONCLUSION: High *b* value is suitable for intestinal DW examination on a high field MR scanner.

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Key words: Crohn's disease; Diffusion-weighted imaging; *b* value; Magnetic resonance image; 3.0 Tesla

Core tip: To date, nearly all the articles regarding diffusion-weighted imaging (DWI) utility in active Crohn's disease chose relatively lower *b* values, and the examinations were finished on 1.5T magnetic resonance (MR) scanners. In our study, we try to investigate the appropriate *b* value of DWI on a high field MR scanner. During scanning, we adopted a low *b* value (800 s/mm²), a high *b* value (1500 s/mm²) and two very high *b* values (2000 and 2500 s/mm²). Our findings suggested that the *b* value of 1500 s/mm² would be appropriate and when DWI was adopted on a 3.0T MR scanner, a high *b* value should be applied.

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INTRODUCTION

Crohn's disease (CD) is a chronic and relapsing inflammatory disorder of unknown cause that affects mainly young people^[1]. Because of its broad availability and high spatial resolution, computed tomography (CT) based imaging, especially CT enterography, has become the most widely used cross-sectional imaging technology for Crohn's disease^[2]. Growing concern about the flaw intrinsic to CT technology is the radiation utilized to generate the images. Magnetic resonance enterography, which offers the advantage of multi-planar capability and lacks ionizing radiation has proven to be a clinically useful technique for the evaluation of CD, particularly in younger patients^[3]. Diffusion-weighted imaging (DWI) has been widely used for intracranial diseases and for the evaluation of various abdominal organs with increasing frequency in recent years^[4-6]. It derives its image contrast from differences in the motion of water molecules between tissues^[7]. The *b* value refers to the strength of the diffusion sensitizing gradient. The sensitivity of the diffusion sequence is adjusted by varying the *b* value, which is most readily achieved by altering the gradient amplitude.

High *b* value DWI was commonly used in the evaluation of the central nervous system. The *b* values applied in the stroke studies with DWI could reach 1500 to 5000 s/mm²^[8]. In abdominal MR examinations, *b* value 2000 s/mm² was reported in prostate cancer detection^[9,10] and 1000 s/mm² was reported in pancreatic neuroendocrine tumor diagnosis^[11]. To date, there were only a few articles about the utility of DWI for patients with active Crohn's disease. Each of them chose a relatively lower *b* value, and the examinations were finished on 1.5-T MR scanners. None of these articles adopted a *b* value higher than 1000 s/mm²^[12-14].

The purpose of our study was to determine the optimal *b* value when DWI was adopted in 3.0-T MR scanning for detecting active inflammation in patients suffering from Crohn's disease.

MATERIALS AND METHODS

Patients

From September 2010 to October 2011, 31 CD patients clinically diagnosed with active inflammation were referred for MR examination. There were 20 men and 11 women enrolled in this study with a mean age of 28 years (range 17 to 63 years). Clinical activity was assessed based on the following criteria: (1) Crohn's disease activity index > 150 (Table 1); (2) C-reactive protein (CRP) > 8 mg/L; and (3) erythrocyte sedimentation rate (ESR) > 20 mm/h. All the patients accepted small and large intestinal endos-

Table 1 Crohn's disease activity index

Signs and symptoms	Multiplication factor
Number of liquid or very soft stools per day in a week	2
Abdominal pain (0 = none; 1 = mild; 2 = moderate; 3 = severe)	5
Number of complications	20
Taking loperamide/opiates for diarrhea (0 = no, 1 = yes)	30
Abdominal mass (0 = none, 2 = questionable, 5 = definite)	10
Hematocrit: male (47-Hct); female (42-Hct)	6
Percentage below predicted body weight	1
Evaluation	< 150: remission 150-450: moderate-severe > 450: very serious

copy. The small intestinal endoscopy was conducted *via* a per-anal route. Institutional review board approval was obtained and informed consent was waived for this retrospective study, which complied with the Health Insurance Portability and Accountability Act of 1996.

MR protocol

The MR imaging examination was performed using a 3.0-T GE scanner (Signa Excite; GE HealthCare, Milwaukee, WI, United States). Patients fasted for 8 h before MR examinations and took 1000 mL solution of Polyethylene Glycol Electrolyte Powder (Wanhe Inc., Shenzhen, China) to clean the small and large intestine. About an hour before MR scanning, another 1000 mL solution of Polyethylene Glycol Electrolyte Powder was administered orally to each patient. Scopolamine 10 mg (Shanghai Xinyi Pharmaceuticals Co., Ltd., Shanghai, China) was administered intramuscularly 10 min before the examination started. All patients were routinely scanned with an 8-channel, phased-array body coil in the supine position. All sequences except T1W imaging were scanned using the respiratory-triggering technique.

T2-weighted single shot fast spin-echo images were acquired in axial and coronal planes. The scan parameters were as follows: TR/TE, 2000-3400/68 ms; slice thickness, 5 mm; interslice gap, 0 mm; matrix, 384 × 192; FOV, 42 cm × 25 cm; NEX, 0.6; SENSE factor, 2. Axial T1-weighted three-dimensional fast spoiled gradient echo was acquired with the breath-holding technique: TR/TE, 310/2.5 ms; slice thickness, 6 mm; interslice gap, 0 mm; matrix, 288 × 192; FOV, 35 cm × 25 cm; NEX, 0.5; SENSE factor, 2.

Diffusion-weighted MR images were acquired in the transverse plane using the single-shot echo planar imaging technique with parallel imaging and fat suppression (spectral attenuation inversion recovery). Scan parameters were as follows: TR/TE, 5820-6200/74-78 ms; slice thickness, 6 mm; interslice gap, 2 mm; matrix, 128 × 96; FOV, 40 cm × 28 cm; NEX, 4. The frequency direction was left to right. Diffusion-encoding gradients were applied as 5 *b* values from 0 to 2500 s/mm² (0, 800, 1500,

Table 2 Mean contrast-to-noise ratios of four *b* value diffusion-weighted imaging sequences

	<i>b</i> = 800	<i>b</i> = 1500	<i>b</i> = 2000	<i>b</i> = 2500
<i>b</i> = 800	79.30 ± 34.59	<i>P</i> = 0.006	<i>P</i> < 0.01	<i>P</i> < 0.01
<i>b</i> = 1500	<i>P</i> = 0.006	57.66 ± 23.95	<i>P</i> = 0.007	<i>P</i> = 0.003
<i>b</i> = 2000	<i>P</i> < 0.01	<i>P</i> = 0.007	36.52 ± 14.95	<i>P</i> = 0.820
<i>b</i> = 2500	<i>P</i> < 0.01	<i>P</i> = 0.003	<i>P</i> = 0.820	34.78 ± 24.83

Unit of *b* value in diffusion-weighted imaging is s/mm².**Table 3** Mean signal-to-noise ratios of four *b* value diffusion-weighted imaging sequences

	<i>b</i> = 800	<i>b</i> = 1500	<i>b</i> = 2000	<i>b</i> = 2500
<i>b</i> = 800	113.98 ± 48.92	<i>P</i> = 0.007	<i>P</i> < 0.01	<i>P</i> < 0.01
<i>b</i> = 1500	<i>P</i> = 0.007	84.77 ± 33.24	<i>P</i> = 0.004	<i>P</i> = 0.001
<i>b</i> = 2000	<i>P</i> < 0.01	<i>P</i> = 0.004	53.58 ± 23.45	<i>P</i> = 0.567
<i>b</i> = 2500	<i>P</i> < 0.01	<i>P</i> = 0.001	<i>P</i> = 0.567	47.58 ± 29.67

Unit of *b* value in diffusion-weighted imaging is s/mm².**Table 4** Apparent diffusion coefficient values of four *b* value diffusion-weighted imaging sequences

<i>b</i> value (s/mm ²)	ADC value (× 10 ⁻³ mm ² /s)		<i>P</i> value
	Inflammatory segments	Normal segments	
800	1.38 ± 0.28	2.00 ± 0.38	< 0.01
1500	1.09 ± 0.20	1.50 ± 0.28	< 0.01
2000	0.95 ± 0.19	1.34 ± 0.28	< 0.01
2500	0.88 ± 0.14	1.20 ± 0.21	< 0.01

ADC: Apparent diffusion coefficient.

2000 and 2500 s/mm²) along the three orthogonal directions of motion-probing gradients. The apparent diffusion coefficient (ADC) maps were automatically constructed on a pixel-by-pixel basis. Each DWI acquisition time was less than 5 min. The whole acquisition time of the entire examination for each patient was approximately 40 min depending on the patients' respiratory rates.

Qualitative analysis

Image evaluation was performed on a workstation (GE Healthcare, AW4.2). All images were evaluated by two experienced gastrointestinal radiologists (4 and 6 years of experience) who were both blinded to clinical details, as well as endoscopic results. For any disagreement in the data analysis, a joint reading session was performed to reach consensus.

Eight intestinal segments were evaluated for each patient: proximal ileum (30-130 cm up to the ileocecal valve), distal ileum (10-30 cm up to the ileocecal valve), terminal ileum (10 cm up to the ileocecal valve), ascending colon, transverse colon, descending colon, sigmoid colon, and rectum. On DW images, the intestinal segment was evaluated as positive when it demonstrated significant high signal intensity on DWI and low signal intensity on ADC map. The DWI findings were com-

pared with endoscopic results.

The manifestation of intestinal anatomic structure on DWI was evaluated on a three-point scale as follows: 0 = both inflammatory and normal intestinal wall structures were clear, 1 = inflammatory intestinal wall structure was clear while partial normal intestinal wall structure was vague, 2 = only partial positive or negative intestinal wall structure could be identified.

Quantitative analysis

The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) in all four different *b* value groups were measured. Image noise was measured from a large area (approximately 260 cm²) outside the abdominal parenchyma and defined as the standard deviation of background signal intensity. The signal contrast and ADCs were measured on both normal and inflammatory bowel walls when these images were properly magnified, and region of interest (ROI) areas were determined as large as possible. On DW images, ROIs were placed on the segments where the signal was the brightest.

Statistical analysis

Statistical analysis was performed using SPSS 11.5. Continuous variables are expressed as mean ± standard deviation and categorical variables as frequencies or percentages. The comparisons of CNR, SNR and ADCs were performed using one-way ANOVA. The diagnostic effect between different *b* value groups was assessed using the χ^2 test.

RESULTS

In the current study, a total of 248 intestinal segments were evaluated, including 85 positive segments and 163 negative segments. The positive segments included 4 proximal ileum segments, 7 distal ileum segments, 15 terminal ileum segments, 14 ascending colon segments, 10 transverse colon segments, 11 descending colon segments, 11 sigmoid colon, and 13 rectum segments.

Considering the visual image quality of DWI, when *b* value 800 s/mm² was adopted, all cases were evaluated as scale 0. When *b* value 1500 s/mm² was chosen, 4 cases were evaluated as scale 1 and the other 27 cases as scale 0. When *b* value 2000 s/mm² was chosen, 8 cases were evaluated as scale 1, while the other 23 cases were evaluated as scale 2. When *b* value 2500 s/mm² was chosen, all cases were evaluated as scale 2.

Mean and standard deviation values of measured SNR and CNR are summarized in Tables 2 and 3. The SNR was decreased by 25.63% on *b* value 1500 s/mm², 52.99% on *b* value 2000 s/mm² and 58.26% on *b* value 2500 s/mm² images *vs* that on *b* value 800 s/mm² images. The CNR was decreased by 27.28% on *b* value 1500 s/mm², 46.05% on *b* value 2000 s/mm² and 56.14% on *b* value 2500 s/mm² images *vs* that on *b* value 800 s/mm² images. This finding suggested that significant differences did exist in mean SNR (*F* = 17.074, *P* < 0.01) and

Table 5 Overall diagnostic assessment of active Crohn's lesions on diffusion-weighted imaging

<i>b</i> value (s/mm ²)	TP	FP	FN	TN	Sensitivity	Specificity	Lesion detection rate
800	71	20	12	145	83.53%	88.96%	87.10%
1500	69	8	16	155	81.18%	95.10%	90.32%
2000	62	9	23	154	72.94%	94.48%	87.10%
2500	55	8	30	155	64.71%	95.10%	84.68%

TP: True positive; FP: False positive; FN: False negative; TN: True negative. Unit of *b* value in diffusion-weighted imaging is s/mm².

mean CNR ($F = 14.920$, $P < 0.01$), except for the group comparison between *b* value 2000 s/mm² and 2500 s/mm².

The ADCs are shown in Table 4. No matter which *b* value was chosen, the ADCs of the inflammatory intestinal segments were significantly lower than those of the normal segments.

The diagnostic assessment of inflammatory segments on DW images is shown in Table 5. There was no significant difference in lesion detection rate between *b* value 800 s/mm² and *b* value 1500 s/mm² ($\chi^2 = 1.288$, $P = 0.256$), between *b* value 800 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 0$, $P = 1.0$), or between *b* value 800 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 0.599$, $P = 0.439$). There was also no significant difference between *b* value 1500 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 1.288$, $P = 0.256$), or between *b* value 2000 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 0.599$, $P = 0.439$) (Figures 1 and 2).

There was no significant difference in diagnostic sensitivity between *b* value 800 s/mm² and *b* value 1500 s/mm² ($\chi^2 = 0.162$, $P = 0.687$), between *b* value 800 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 2.798$, $P = 0.094$), between *b* value 1500 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 1.630$, $P = 0.202$), or between *b* value 2000 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 1.343$, $P = 0.246$), while a significant difference did exist between *b* value 800 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 7.850$, $P = 0.005$), and between *b* value 1500 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 5.842$, $P = 0.016$). There was no significant difference in diagnostic specificity between *b* value 800 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 3.271$, $P = 0.071$), between *b* value 1500 s/mm² and *b* value 2000 s/mm² ($\chi^2 = 0.062$, $P = 0.803$), between *b* value 1500 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 0$, $P = 1.0$), or between *b* value 2000 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 0.062$, $P = 0.803$), while a significant difference did exist between *b* value 800 s/mm² and *b* value 1500 s/mm², and between *b* value 800 s/mm² and *b* value 2500 s/mm² ($\chi^2 = 4.179$, $P = 0.041$).

DISCUSSION

The utility of DWI for gastrointestinal examination relatively falls behind the utility for other parenchymal organs in abdomen. So far, DWI is usually acquired in rectal cancer evaluation at relatively high *b* value (1000 s/mm²), especially during postoperative follow-up for the detection of local recurrence^[15-17]. As far as the bowel inflammation was concerned, most examinations were completed us-

ing a 1.0- or 1.5-T MR scanner and the *b* values of DWI sequences were relatively lower. Oto *et al*^[12] reported that dynamic contrast-enhanced MRI and DWI provide quantitative measures of small bowel inflammation that can differentiate active inflammatory small bowel segments from normal segments in CD patients with *b* values 0 and 600 s/mm². It was also reported that three *b* values (0, 100 and 800 s/mm²) could be used with axial images through the upper and lower abdomen obtained in Crohn's disease^[18]. Neubauer *et al*^[19] reported the utility of DWI in children and young adults suffering from Crohn's disease with *b* values 50 and 800 s/mm². It is obvious that the optimal *b* value of MR intestinal scanning was still in argument and no trial of *b* value higher than 1000 s/mm² was conducted, especially on a high field MR scanner.

In this study, the ADCs of the active inflammatory segments were lower than those of the normal bowel segments in all DWI sequences. It was demonstrated that no matter which *b* value was chosen, a significant difference was detected ($P < 0.01$), although it is also suggested that there was no way to tell which *b* value was better through ADC measurement individually.

When quantitative analysis of image quality was concerned, it was confirmed that SNR and CNR were the best when *b* value 800 was chosen. When higher *b* values (2000 or 2500 s/mm²) were adopted, SNR and CNR of DWI images apparently declined. Burdette increased the number of excitations to maintain SNR at high *b* values^[20], while we did not change the number of excitations in order to make reliable comparisons. When qualitative analysis of image quality was concerned, *b* = 2000 or 2500 s/mm² was not satisfied for diagnostic requirement.

It was suggested that when low *b* value was chosen, the diagnostic sensitivity was higher while the specificity was lower. The diagnostic sensitivity decreased and the specificity increased when higher *b* value was adopted.

Kim *et al*^[10] reported that DW imaging with a *b* value of 1000 s/mm² was more sensitive and more accurate in localizing prostate cancer than DW imaging with a *b* value of 2000 s/mm² on a 3.0-T MR scanner. However, some studies focused on high *b* value DWI in ischemic stroke supported that high *b* values might increase the diagnostic sensitivity in patients with hyper-acute infarction^[21-23]. In our study, a *b* value of 800 s/mm² had the best diagnostic sensitivity, while its false positive rate was also higher, which was due to the fact that the signal in-

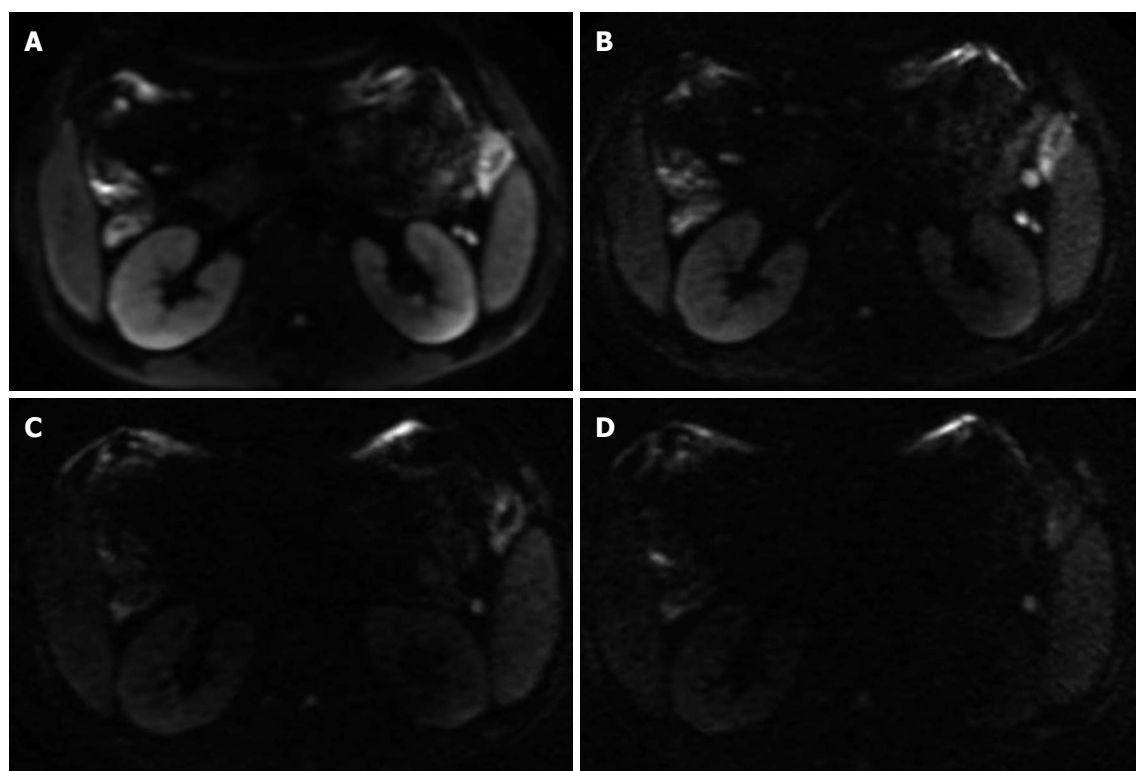


Figure 1 Diffusion-weighted imaging images obtained in a 28-year-old man. The whole colonic inflammation was identified by endoscopy. The high signal intensity of colonic liver flexure and splenic flexure could be recognized on $b = 800 \text{ s/mm}^2$ (A) and $b = 1500 \text{ s/mm}^2$ images (B). But when $b = 2000 \text{ s/mm}^2$ or $b = 2500 \text{ s/mm}^2$ (C and D) was chosen, the signal intensity was depressed and these two segments were misdiagnosed as negative.

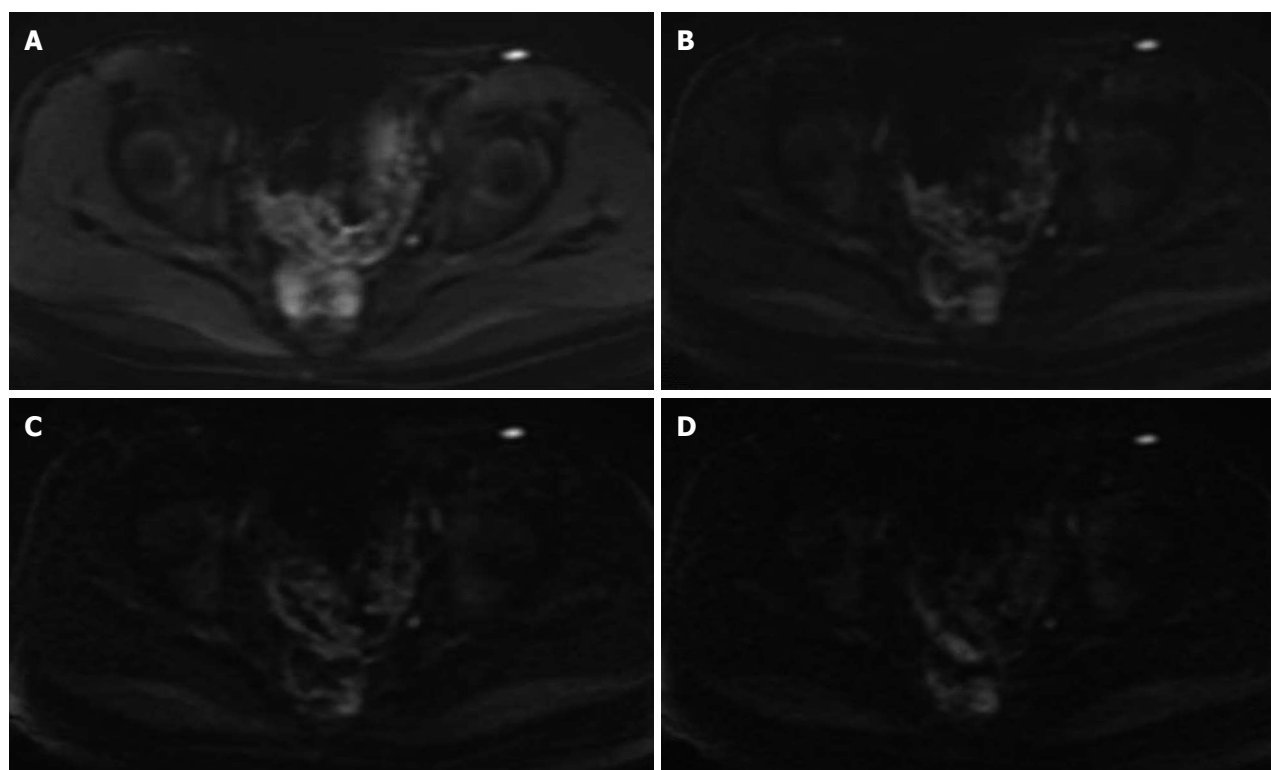


Figure 2 Images obtained in a 34-year-old man. There was high signal intensity in the sigmoid colon and rectum when b value 800 s/mm^2 (A) was chosen. But when b value 1500 s/mm^2 to 2500 s/mm^2 (B-D) was chosen, the high signal was apparently depressed. It was confirmed that the sigmoid colon and rectum were normal by colonic endoscopy.

tensity of normal intestine was not suppressed enough. Therefore, although the image quality and diagnostic sensitivity were pretty good when b value 800 s/mm^2 was adopted, the lesion detection rate was not good because its diagnostic specificity was not satisfied. The false high signal intensity of normal intestinal segments might be partially due to the mucus covering the intestinal mucosa. It is possible that the utility of higher b values might increase diffusion specificity by diminishing the hyper-intensity in intestinal lumen with long T2 relaxation times and suppress the high signal of intestinal wall caused by normal mucosa. When b value became higher and higher (1500 s/mm^2 to 2500 s/mm^2), diagnostic specificity was not apparently increased and diagnostic accuracy decreased because of the unsatisfied sensitivity. The reason might be that in some high b value cases (especially 2000 s/mm^2 or 2500 s/mm^2), the signal intensity, even that of inflammatory lesion was suppressed. The poor image quality could be part of the reasons, while the major contributor was still required to be explored. Overall, it was concluded that when a b value of 1500 s/mm^2 was chosen, the diagnostic specificity and sensitivity were appropriate and the diagnostic accuracy was the highest (Figures 1 and 2).

In conclusion, a b value of 1500 s/mm^2 offered the best balance of image quality and diagnostic requirement in this current study.

A limitation of this study was its relatively small sample size. Only 31 patients were included. Furthermore, the small intestinal endoscopy was conducted *via* a per-anal route, and the farthest reach was the proximal ileum not including the jejunum. So the diagnostic effect of DWI on active CD lesions in the upper digestive tract was still required to be discussed. In addition, only four b values were chosen in this study and the average interval was 500 to 700 s/mm^2 . It is possible that the best b value could be found around 1500 s/mm^2 with a smaller interval.

COMMENTS

Background

Crohn's disease (CD) is a chronic and relapsing inflammatory disorder of unknown cause that affects mainly young people. Because of its broad availability and high spatial resolution, computed tomography (CT) based imaging, especially CT enterography, has become the most widely used cross-sectional imaging technology for Crohn's disease.

Research frontiers

The utility of diffusion-weighted imaging (DWI) for gastrointestinal examination relatively falls behind the utility for other parenchymal organs in abdomen. So far, DWI is usually acquired in rectal cancer evaluation at relatively high b values (1000 s/mm^2), especially during postoperative follow-up for the detection of local recurrence.

Innovations and breakthroughs

Authors try to investigate the appropriate b value of DWI on a high field MR scanner. During scanning, we adopted a low b value (800 s/mm^2), a high b value (1500 s/mm^2) and two very high b values (2000 and 2500 s/mm^2). It was suggested that the b value of 1500 s/mm^2 would be appropriate and when DWI was adopted on a 3.0-T MR scanner, a high b value should be applied. High b value is suitable for intestinal DW examination on high field MR scanners.

Peer review

This is a small study of 30 patients who were scanned on a 3.0-T MR scanner

for detecting colonic inflammation in patients with active CD. The author's goal is to determine the optimal b value for those patients.

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