学位論文（博士）

Evaluation of diffusion-weighted magnetic resonance imaging of the rectal cancers: comparison between modified reduced field-of-view single-shot echo-planar imaging with tilted two-dimensional radiofrequency excitation pulses and conventional full field-of-view readout-segmented echo-planar imaging

（直腸癌の拡散強調 MRI での評価：
傾斜二次元高周波励起パルスを用いた
縮小視野 SS-EPI 法と全視野 RS-EPI 法の比較）

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令和６年１１月

学位論文の関連論文の研究背景及び要旨

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〔題名〕

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〔研究背景〕

MRI の拡散強調画像（diffusion-weighted imaging : DWI）は、大腸癌の検出や局在診断に有用であることが知られており、化学放射線療法に対する反応性の予測や、apparent diffusion coefficient（ADC）値に基づく非侵襲的マーカーとしても有用であると報告されている。しかしながら、single-shot echo-planar imaging (SS-EPI)を用いた従来の DWI は、体動や磁場の不均一性、腸管ガスによる磁化率アーチファクト等の影響を受けやすく、歪みや画像のぼやけが生じやすい。

Readout segmented (RS)-EPI を用いた DWI は、k 空間を読み出し方向に沿っていくつかのセグメントに分割し、エコー間隔を短くすることで、従来の SS-EPI を用いた DWI と比較して、歪みの減少、分解能の向上を可能にした。一方、RS-EPI を用いた DWI の欠点として、撮影時間が長くなることが挙げられる。

近年、2D 選択的 radiofrequency （RF）パルスを用いて位相エンコード方向の field-of-view (FOV)を縮小した SS-EPI ベースの DWI が開発され、腹部 MRI 検査に応用されている。この FOV を縮小（reduced FOV）した DWI（r-DWI）法は、小さな矩形領域を直接励起することができ、通常の FOV（full-FOV）を用いた DWI（f-DWI）と比較して、空間分解能が向上し、体動や腸内ガスに関連するゴーストや磁化率アーチファクトの少ない画像が得られる。しかし、位相エンコード方向の折り返しアーチファクトは、2D RF パルスの側方励起により、完全には除去できないことが多い。この問題に対処するため、励起面を傾斜させた 2D 選択的 RF パルスを用いた r-DWI（tilted r-DWI）が提案されており、不要な側方励起を画像平面とスライスの間の死角に移動させることにより、位相エンコード方向の折り返しアーチファクトを除去することができる。

tilted r-DWI はさまざまな領域で画質を改善することが示されているが、直腸癌の画像診断における有用性はまだ評価されていない。そこで本研究では、直腸癌に対する tilted r-DWI

の画質を定性的、定量的に評価し、画質と見かけの拡散係数（ADC）値を、RS-EPI を用いた f-DWI と比較する。

〔要旨〕

対象と方法：

2020 年 11 月から 2022 年 5 月までの間に MRI で f-DWI と tilted r-DWI の両方が撮像された患者で、外科的切除または内視鏡ガイド下生検で直腸癌の病理診断を受けた 22 名の患者（男性 13 人、女性 9 人、平均年齢 72.0±2.3 歳、範囲 46-87 歳）を対象とした。

3 テスラの MRI（MAGNETOM Prisma または Skyra、Siemens Healthcare）を使用した。

定性評価では、MR シーケンスの種類および臨床データについて盲検化された f-DWI および tilted r-DWI の各データセットを、3 名の放射線科医が独立して解析を行った。アーチファクトや画質などの以下のパラメータについて 4 段階評価で評価した：ゴースト／モーションアーチファクト・磁化率アーチファクト・折り返しアーチファクト（1＝重度、2＝中等度、3＝軽度、4＝なし）、直腸の解剖学的描出（1=不良、2=中等度、3=良好、4=きわめて良好）、スライス間信号の均一性・全体的な画質(1＝ 不良、 2＝ 普通、 3＝ 良好、4＝優れている）、および直腸病変の明瞭度（1＝ 病変が検出できない、2＝ 病変と背景のコントラストが認識できる、3 ＝ 病変と背景のコントラストが中程度または高コントラストだが病変の辺縁が不明瞭、4＝ 病変と背景のコントラストが優れており病変の辺縁が明瞭）とした。3 人の読影者の間で意見の相違が生じた場合、合議制により最終決定が行われた。

定量評価では、各画像上に関心領域（Region of Interest：ROI）を配置して直腸癌と直腸壁の信号強度（signal intensity ：SI）と標準偏差（standard deviation：SD）を測定し、信号対雑音比（signal-noise ratio：SNR）、コントラスト対雑音比（contrast-noise ratio：CNR）、信号強度比（signal intensity ratio : SIR）を下記の計算式を用いて計算した。背景空気の SD も測定し、SNR 算出に用いた。SNR は直腸病変の SI と背景空気の SD の比として計算した。CNR は病変部と正常直腸組織の SI 差の絶対値を病変部と正常直腸組織の標準偏差で割った比と定義した。SIR は直腸病変と正常直腸組織の SI の比として計算した。また、各画像に対応する ADC マップ上に ROI を配置することで、直腸病変の ADC 値を測定した。一人の放射線科医がすべての ROI 計測を行い、ROI 配置の記録を保存し、その妥当性を別の放射線科医が検証した。

$$SNR = \frac{SItumor}{SDbackground} \qquad CNR = \frac{|SI_{tumor} - SI_{tissue}|}{\sqrt{SD_{tumor}{}^2 + SD_{tissue}{}^2}} \qquad SIR = \frac{SItumor}{SI_{tissue}}$$

SI_{tumor}： 腫瘍部の信号平均　　SI_{tissue}: 正常直腸粘膜の信号平均

$SD_{background}$: 背景信号の標準偏差　　SD_{tissue}: 正常直腸粘膜の信号標準偏差

結果：

定性的評価（表 1）では、以下の画質スコアは tilted r-DWI の方が RS-EPI を用いた f-DWI よりも有意に高かった（すべて p＜0.01）：直腸の解剖学的描出、3(1) vs. 2(1)；信号の均一性、3(0) vs. 2(1)；ゴーストアーチファクトの有無、3(0) vs. 2(1)；磁化率アーチファクトの有無、3(1) vs. 2(0)；直腸病変の明瞭度 4(1) vs. 3(1)；全体的な画質 3(1)対 2(0)であった。tilted r-DWI と RS-EPI を用いた f-DWI では、折り返しアーチファクトに関して有意差はなかった［4（0）対 4（0）］。

表 1. tilted r-DWI と RS-EPI を用いた f-DWI の画質比較.

	f-DWI with RS-EPI	tilted r-DWI	*p* value
直腸の解剖学的描出	2 (1)	3 (1)	< 0.01*
スライス間信号の均一性	2 (1)	3 (0)	< 0.01*
ゴーストアーチファクト	2 (1)	3 (0)	< 0.01*
磁化率アーチファクト	2 (0)	3 (1)	< 0.01*
折り返しアーチファクト	4 (0)	4 (0)	N.S.
直腸病変の明瞭度	3 (1)	4 (1)	< 0.01*
全体的な画質	2 (0)	3 (1)	< 0.01*

数値は中央値（四分位範囲）で記載　　*有意差あり

定量的評価（表 2）では、tilted r-DWI の CNR は RS-EPI を用いた f-DWI よりも有意に高かった（4.92±2.73 vs 3.58±2.04、p＜0.01）。SNR と SIR は、tilted r-DWI の方が RS-EPI を用いた f-DWI よりも高い傾向があったが、有意差は見られなかった（SNR：130±107 vs. 123±80、p = 0.86、CNR；2.63±1.07 vs 2.32±0.90、p = 0.15）。ADC 値に関しては、tilted r-DWI から算出した直腸癌の平均 ADC 値と RS-EPI を用いた f-DWI から算出した直腸癌の平均 ADC 値との間に有意差は認められなかった（921±162 vs. 898±134, p = 0.29）。

表 2. tilted r-DWI と RS-EPI を用いた f-DWI の CNR、SNR、SIR 及び ADC 値の比較.

	f-DWI with RS-EPI	r-DWI	*p* value
CNR	3.58 ± 2.04	4.92 ± 2.73	< 0.01*
SNR	123 ± 80	130 ± 107	0.86
SIR	2.32 ± 0.90	2.63 ± 1.07	0.15
ADC	898 ± 134	921 ± 162	0.29

数値は中央値±標準偏差で記載　　*有意差あり

考察:

RS-EPI を用いた f-DWI と比較して、2D 選択的 RF パルスを用いて位相エンコード方向の FOV を縮小した tilted r-DWI は、縮小した FOV 外の皮下脂肪の影響を排除することによりゴーストアーチファクトを減少させ、直腸以外の消化管をできる限り FOV 外とすることで空気−組織界面を減少させることにより磁化率アーチファクトを最小化し、励起面を傾斜させることにより折り返しアーチファクトを防止し、より高い面内空間分解能により視認性を改善したと考えられる。折り返しアーチファクトに関しては、tilted r-DWI と f-DWI の間に有意差は認められず、両シーケンスとも全例で最高スコアの 4 が得られた。先行研究においては、FOV を小さくしたシーケンスでは、2D 選択的 RF パルスを併用してもしばしば折り返しアーチファク

トを生じることが報告されているが、我々の研究により tilted r-DWI では FOV を縮小しても折り返しアーチファクトが出現しないことが示された。

定量評価では、tilted r-DWI と f-DWI の SNR に有意差は認められなかった。SNR は FOV が小さくなるにつれて低下するという過去の報告がいくつかあるが、今回の結果とは矛盾する。理論的には、FOV が小さくなり画像の空間分解能が高くなると SNR は低下するが、本研究では SNR の低下を補うために傾斜 r-DWI では励起数を増やすことで（NEX=6）、f-DWI と同等の SNR を維持していると考えられる。実際、統計的な有意差は示されなかったが、直腸癌の SIR も増加した。一方で、RS-EPI を用いた f-DWI と比較して tilted r-DWI では CNR が有意に高く、これは先行研究と一致している。tilted r- DWI で CNR が増加したのは、直腸癌の信号を強調するために励起回数を増やしたためと考えられる。また、tilted r-DWI では RS-EPI を用いた f-DWI よりも TE がわずかに長いことで、T2 コントラストが上昇し、その結果 tilted r-DWI では直腸癌と直腸壁との信号差が増大し、CNR が高くなる可能性も挙げられる。ADC 値の評価に関しては、RS-EPI を用いた f-DWI と tilted r-DWI の間に有意差は認められなかった。このことから、tilted r-DWI で測定された ADC 値は、先行研究で示された ADC 値に関する研究結果と同様に、化学放射線療法に対する反応性の予測、あるいは腫瘍の非侵襲的マーカーとして使用できる可能性が示唆された。

結語：2D 選択的 RF パルスを用い、位相エンコード方向の FOV を小さくした tilted r-DWI は、RS-EPI を用いた f-DWI よりもアーチファクトが少なく画質が改善し、直腸病変の描出性も高いことから、臨床における直腸癌の評価に有用であることが示された。

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ABDOMINAL RADIOLOGY

Evaluation of diffusion-weighted magnetic resonance imaging of the rectal cancers: comparison between modified reduced field-of-view single-shot echo-planar imaging with tilted two-dimensional radiofrequency excitation pulses and conventional full field-of-view readout-segmented echo-planar imaging

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Abstract

Purpose To evaluate the image quality qualitatively and quantitatively, as well as apparent diffusion coefficient (ADC) values of modified reduced field-of-view diffusion-weighted magnetic resonance imaging (MRI) using spatially tailored two-dimensional radiofrequency pulses with tilted excitation plane (tilted r-DWI) based on single-shot echo planar imaging (SS-EPI) compared with full-size field-of-view DWI (f-DWI) using readout segmented (RS)-EPI in patients with rectal cancer.

Materials and methods Twenty-two patients who underwent an MRI for further evaluation of rectal cancer were included in this retrospective study. All MR images were analyzed to compare image quality, lesion conspicuity, and artifacts between f-DWI with RS-EPI and tilted r-DWI with SS-EPI. Signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), and ADC values were also compared. The Wilcoxon signed-rank test or paired *t* test was performed to compare the qualitative and quantitative assessments.

Results All image quality scores, except aliasing artifacts, were significantly higher ($p < 0.01$ for all) in tilted r-DWI than f-DWI with RS-EPI. CNR in tilted r-DWI was significantly higher than in f-DWI with RS-EPI ($p < 0.01$), while SNR was not significantly different. Regarding the ADC values, no significant difference was observed between tilted r-DWI and f-DWI with RS-EPI ($p = 0.27$).

Conclusion Tilted r-DWI provides a better image quality with fewer artifacts and higher rectal lesion conspicuity than f-DWI with RS-EPI, indicating the feasibility of this MR sequence in evaluating rectal cancer in clinical practice.

Keywords Rectal cancer · Diffusion-weighted imaging · Reduced field-of-view · Tilted excitation

Introduction

Several studies demonstrated that diffusion-weighted MR imaging (DWI) could help detect, localize, and further characterize colorectal cancers using either visual evaluation of images or apparent diffusion coefficient (ADC) measurement in clinical practice [1]. DWI can also be useful in predicting response to neoadjuvant chemoradiation therapy or as a noninvasive marker of tumor aggressiveness based on ADC values [2–4]. However, conventional DWI using a single-shot echo-planar imaging (SS-EPI) sequence has limited spatial resolution and is sensitive to motion, magnetic field inhomogeneity, and susceptibility artifacts from bowel gas,

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leading to geometrical distortion and image blurring and obscuring the primary rectal cancers.

Readout segmented (RS)-EPI using a readout segmentation of long variable echo-trains (RESOLVE) technique has been an alternative sequence for DWI [5]. The RS-EPI sequence is based on segmenting a k-space into several segments along the readout direction to shorten the echo spacing [5]. As a consequence, DWI with RS-EPI exhibits reduced spatial distortion, improved resolution, and susceptibility sensitivity compared with DWI using the SS-EPI sequence [6]. Several previous studies demonstrated that DWI based on RS-EPI is a clinically promising technique to improve the image quality for evaluating lesions in patients with rectal cancer compared with DWI using the SS-EPI sequence [7–9]. Meanwhile, one of the disadvantages of DWI with RS-EPI was the increased acquisition time because the k-space is partitioned into several adjacent segments along the readout-encoding direction, and each segment in the k-space requires a separate acquisition [6].

SS-EPI-based DWI sequences performed with a reduced field-of-view (FOV) in phase-encoding direction technique using two-dimensional (2D) spatially selective radiofrequency (RF) excitation pulses has been developed and recently applied to abdominal MR examinations [10–13]. This reduced FOV DWI (r-DWI) technique allows direct excitation of small rectangular areas and provides high-quality images with improved spatial resolution and less ghosting and susceptibility artifacts related to motion and intestinal gas compared to conventional full-size FOV DWI (f-DWI) [14–17]. However, aliasing artifacts in the phase-encoding direction can often not be entirely eliminated due to side excitations of the finitely sampled 2D RF pulse [18]. To address this, modified r-DWI using spatially tailored 2D RF pulses with a tilted excitation plane (tilted r-DWI) have been suggested, where aliasing artifacts in the phase-encoding direction can be eliminated by moving the unwanted side excitations in the blind spot between the image plane and slices [14, 19]. While tilted r-DWI has been shown to achieve improved image quality in different body areas [20–22], its utility has not been assessed yet for imaging of rectal cancer. Therefore, this study aims to evaluate the image quality qualitatively and quantitatively and the apparent diffusion coefficient (ADC) values of tilted r-DWI for rectal cancer compared with f-DWI using RS-EPI.

Materials and methods

Study population

Our institutional review board approved this study, which involved only retrospective analysis of existing clinical datasets, and the need for informed consent was waived from all patients. A cross-referenced search of the database of radiology and pathology was performed to identify all patients with histologically proven rectal cancer who underwent pelvic MR examinations between November 2020 and May 2022. The following inclusion criteria were utilized: (1) patients receiving both f-DWI (RESOLVE) and tilted r-DWI in preoperative MRI and (2) patients having a pathological diagnosis of rectal cancer by surgery resection or endoscopy-guided biopsy. The exclusion criteria were as follows: (1) patients having neoadjuvant therapy, including chemoradiotherapy before MR examinations, and (2) patients with extremely poor image quality intolerable for evaluation due to patient movement. Based on these criteria, the study group included 22 patients (13 males; 9 females; mean age, 72.0 ± 2.3 years; range, 46–87 years) (Fig. 1). The median time interval between MRI and surgery/biopsy was 11.5 days (range 0–51 days).

MR imaging technique

All MR procedures were performed using a 3 T clinical scanner (MAGNETOM Prisma or Skyra, Siemens Healthcare, Erlangen, Germany) with an 18-channel body array coil and a 32-channel spine coil in supine position. No bowel preparation or intravenous antispasmodic agents were administered before the MR examination. The routine imaging protocol for all patients with rectal cancer included both f-DWI with a full-size FOV using the RESOLVE technique and a tilted r-DWI (prototype sequence) with a reduced-size FOV using the spatially tailored 2D RF pulses with tilted excitation plane.

The f-DWI was obtained covering the pelvic space from 10 cm below the symphysis pubis to the level of the sacral promontory using the following parameters: FOV: 300 × 226 mm^2, acquisition matrix: 180 × 109, repetition time (TR): 10,000 or 10,820 ms, echo time (TE): 42 or 52 ms, bandwidth: 926 or 992 Hz/pixel, slice thickness: 3 mm, number of slices: 55, b-values: 0 s/mm^2 [number of excitation pulses (NEX) = 1] and 1000 s/mm^2 (NEX = 1), parallel imaging acceleration factor: 3, and acquisition time: 190 or 206 s.

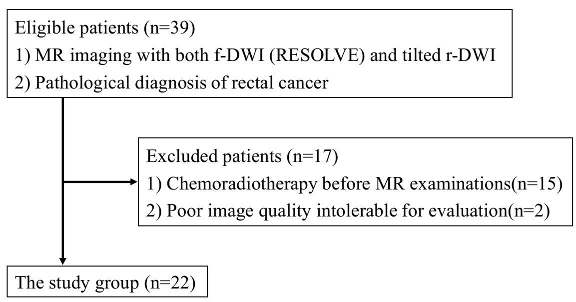

Fig. 1 Flowchart of patient selection

For tilted r-DWI, slightly rotating the excitation plane of the 2D RF pulse enables to avoid infolding artifacts along the phase-encoding direction which are caused by side excitations (12). The following imaging parameters were used for the tilted r-DWI focused on the rectum and surrounding organs: FOV: 250×142 mm^2; matrix: 180×60; TR: 10,000 or 10,800 ms; TE: 49 or 68 ms; bandwidth: 1736 or 1388 Hz/pixel; slice thickness: 3 mm; number of slices: 55; b-values: 0 s/mm^2 (NEX = 3) and 1000 s/mm^2 (NEX = 6); tilting angle for excitation: 10 degree; and parallel imaging acceleration factor: 1, and acquisition time: 220 or 238 s.

Both DW images were obtained during free breathing and acquired during the same session in the axial plane. ADCs maps were automatically calculated and reconstructed. Because the protocols of f-DWI and tilted r-DWI were optimized separately based on our clinical experience, imaging parameters were determined to achieve the diagnostic image quality within the clinically accepted acquisition time (3–4 min per sequence) and not forced to be the same between these two sequences.

Image analysis

Qualitative image analysis

Three experienced radiologists in abdominal MRI (reader 1 = 6 years, reader 2 = 7 years, and reader 3 = 20 years), blinded to the types of MR sequence and any clinical data, independently participated in the qualitative image analysis. The MR images were anonymized by removing patient information and imaging parameters, saved on a clinically dedicated workstation (Shade Quest; FUJIFILM Medical Solutions, Tokyo, Japan), and used for blind reading. Each dataset of f-DWI and tilted r-DWI was randomly analyzed for the following parameters, such as artifacts and image quality using a 4-point scale: presence of ghost/motion artifacts from physiological movement (e.g., respiratory motion or gastrointestinal motility), susceptibility artifacts at the tissue-air interface (e.g., intraintestinal gas), and aliasing artifacts (1 = severe, 2 = moderate, 3 = mild, 4 = absent). Other parameters include anatomical visualization of the rectum (1 = poorly visualized, 2 = fairly visualized with an unsharp margin, 3 = good visualization of the rectum with a sharp margin, 4 = excellent visualization of the rectum), interslice signal homogeneity (i.e., absence of the dark area due to the dielectric effect or eddy current; 1 = poor, 2 = fair, 3 = good, 4 = excellent), overall image quality (1 = poor, considered non-diagnostic; 2 = fair, somewhat impaired diagnostic quality; 3 = good, unimpaired diagnostic quality; 4 = excellent), and rectal lesion conspicuity (1 = lesion not detectable, 2 = merely recognizable lesion-to-background contrast, 3 = intermediate lesion-to-background contrast or high contrast with indistinct lesion margin, 4 = excellent lesion-to-background contrast and a clear lesion margin). If a disagreement occurred among the three readers, the final decision was reached by consensus.

Quantitative image analysis

Signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), and signal-intensity-ratio (SIR) were quantified using operator-defined regions of interest (ROIs) placed on each DW image to measure the signal intensity (SI) and image noise (standard deviation: SD) of rectal cancer and rectal wall. SD of background air was also measured and used for SNR calculation. The ROIs were manually drawn to cover the largest area of the lesion. They were also placed on the normal rectal wall as large as possible, avoiding the intraluminal gas, water, and other contents. The SNR was calculated as the ratio between the mean SI of the rectal lesion (SI_{lesion}) and the SD of background air ($SD_{background\ air}$). The CNR was defined as the ratio of the mean SI difference between lesion (SI_{lesion}) and the normal rectal tissue (SI_{rectum}), divided by the standard deviation of the lesion (SD_{lesion}) and normal rectal tissue (SD_{rectum}). SIR was calculated as the ratio between the mean SI of the rectal lesion (SI_{lesion}) and the normal rectal tissue (SI_{rectum}). ADC measurements of the rectal lesions were conducted by drawing ROIs on ADC maps corresponding to each DW image. One radiologist performed all ROI measurements and saved the record of ROI placement, and its validity was verified by another radiologist.

Statistical analysis

Continuous variables were expressed as means ± standard deviations, whereas categorical variables were presented as medians with interquartile ranges (IQRs) in parenthesis. The Wilcoxon signed-rank test was performed to compare qualitative and quantitative assessments. Inter-reader agreement on visual assessment was calculated by Fleiss kappa statistics and interpreted as follows: slight: 0–0.20; fair: 0.21–0.40; moderate: 0.41–0.60; substantial: 0.61–0.80; and almost perfect: 0.81–1.00 [23]. p-Values < 0.05 were considered to indicate a statistically significant difference. All statistical analyses were performed using SPSS software (version 27.0; IBM, Armonk, NY, USA).

Results

In the qualitative visual assessment (Table 1), the following image quality scores were significantly higher ($p < 0.01$ for all) in tilted r-DWI than in f-DWI with RS-EPI: anatomical visualization of the rectum, 3 (1) vs. 2 (1); signal homogeneity, 3 (0) vs. 2 (1); presence of ghosting artifacts, 3 (0) vs. 2 (1); presence of susceptibility artifacts, 3 (1) vs. 2 (0); rectal

Table 1 Comparison of image quality and conspicuity between f-DWI with RS-EPI and tilted r-DWI

	f-DWI with RS-EPI	Tilted r-DWI	*p* Value
Anatomical visualization of the rectum	2 (1)	3 (1)	< 0.01*
Signal homogeneity	2 (1)	3 (0)	< 0.01*
Presence of ghosting artifacts	2 (1)	3 (0)	< 0.01*
Presence of susceptibility artifacts	2 (0)	3 (1)	< 0.01*
Presence of aliasing artifacts	4 (0)	4 (0)	N.S
Rectal lesion conspicuity	3 (1)	4 (1)	< 0.01*
Overall image quality	2 (0)	3 (1)	< 0.01*

Data are medians with interquartile ranges in parenthesis

*The score for r-DWI is statistically higher than that for f-DWI with RS-EPI

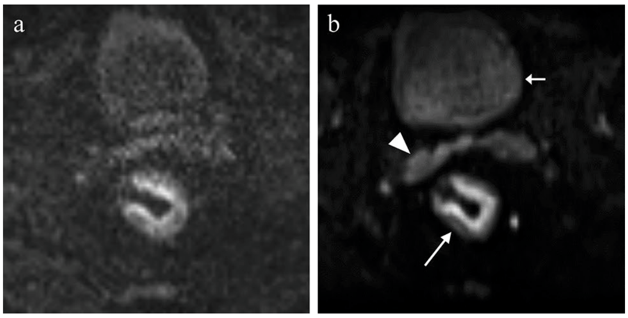

Fig. 2 Example DW image acquired with b = 1000 s/mm^2 in a 72-year-old man with rectal cancer. **a** full-size FOV DWI (f-DWI) with RS-EPI; **b** reduced FOV DWI with tilted excitation plane (tilted r-DWI). Tilted r-DWI showed good conspicuity of the rectal lesion (long arrow). Note that the bladder (short arrow) and the seminal vesicle (arrowhead) were also clearly demonstrated. Overall image quality of tilted r-DWI is better than that of f-DWI with RS-EPI. *RS-EPI* Readout-segmented echo-planar imaging

lesion conspicuity, 4 (1) vs. 3 (1); and overall image quality, 3 (1) vs. 2 (0), respectively (Figs. 2 and 3). There was no significant difference regarding aliasing artifacts [4 (0) vs. 4 (0)] between tilted r-DWI and f-DWI with RS-EPI. Inter-reader agreement on image quality and artifacts was moderate to substantial (anatomical visualization of the rectum of 0.61, signal homogeneity of 0.62, ghosting artifacts of 0.54, susceptibility artifacts of 0.65, aliasing artifacts (N/A), rectal lesion conspicuity of 0.62, and overall image quality of 0.67, respectively).

In the quantitative evaluation (Table 2), CNR in tilted r-DWI was significantly higher than in f-DWI with RS-EPI (4.92 ± 2.73 vs. 3.58 ± 2.04, $p < 0.01$). However, SNR and SIR were not significantly different between tilted r-DWI and f-DWI with RS-EPI (130 ± 107 vs. 123 ± 80, $p = 0.86$,

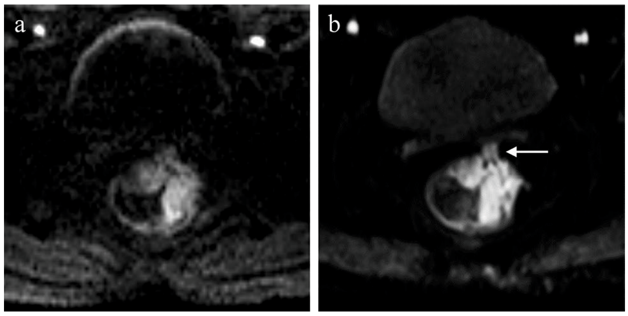

Fig. 3 Example DW image acquired with b = 1000 s/mm^2 in a 72-year-old woman with rectal cancer. **a** full-size FOV DWI (f-DWI) with RS-EPI; **b** reduced FOV DWI with tilted excitation plane (tilted r-DWI). The edge of the tumor extension beyond muscularis propria into perirectal fat (arrow) is more clearly delineated in tilted r-DWI than in f-DWI with RS-EPI. *RS-EPI* Readout-segmented echo-planar imaging

Table 2 Comparison of CNR, SNR and ADC values between f-DWI with RS-EPI and tilted r-DWI

	f-DWI with RS-EPI	r-DWI	*p* Value
CNR	3.58 ± 2.04	4.92 ± 2.73	< 0.01*
SNR	123 ± 80	130 ± 107	0.86
SIR	2.32 ± 0.90	2.63 ± 1.07	0.15
ADC	898 ± 134	921 ± 162	0.29

Data are means ± standard deviations

*Statistically significant difference

and 2.63 ± 1.07 vs. 2.32 ± 0.90, $p = 0.15$, respectively) although SNR and SIR in tilted r-DWI tended to be higher than those in f-DWI with RS-EPI. Regarding the ADC values, no significant difference exists between the mean ADC values of rectal cancer calculated from tilted r-DWI and those from f-DWI with RS-EPI (921 ± 162 vs. 898 ± 134, $p = 0.29$; Table 2).

Discussion

This study demonstrated that tilted r-DWI could provide significantly better image quality with fewer artifacts and higher conspicuity of anatomical structure and rectal cancers than f-DWI with RS-EPI. Compared to f-DWI with RS-EPI, tilted r-DWI using 2D selective RF pulses and reduced FOV in the phase-encoding direction reduced ghosting artifacts by eliminating the effects of subcutaneous fat outside the reduced FOV [24], minimized susceptibility artifacts by reducing the air-tissue interface from the shim volume, prevented aliasing artifacts by tilting the excitation planes, and improved conspicuity provided by higher in-plane spatial resolution. Regarding aliasing artifacts, no significant difference was observed between tilted r-DWI and f-DWI as the highest score of 4 was given in all patients in both sequences. Reduced FOV sequences often suffered from aliasing artifacts, even with the combined use of 2D selective RF pulses [22]. However, our results demonstrated that aliasing artifacts did not appear in tilted r-DWI even when using reduced FOV, indicating the clinical value of using tilted excitation planes in r-DWI using the 2D selective RF pulse.

In the objective evaluation, no significant difference exists in the SNR between tilted r-DWI and f-DWI with RS-EPI. Several previous reports have indicated that SNR decreases with decreasing FOV [25, 26], which is inconsistent with our results. Theoretically, SNR decreases as FOV reduces and image spatial resolution increases. However, in this study, the number of excitations was increased for tilted r-DWI (NEX = 6) to compensate for the lower SNR, presumably maintaining an SNR comparable to that of f-DWI. Furthermore, compared with RS-EPI, a lower parallel imaging factor was used which leads to less g-factor related noise enhancement. In fact, the SIR of rectal cancer also increased, although a statistical difference was not shown. Conversely, CNR was significantly higher in tilted r-DWI compared to f-DWI with RS-EPI, which is consistent with previous studies [27, 28]. The increased CNR in tilted r-DWI will be due to the increased number of excitations to enhance the signal of rectal cancer. Another possibility might be the slightly longer TE in tilted r-DWI than in f-DWI with RS-EPI, which increases the underlying T2-weighting and might therefore increase the signal difference between the rectal cancers and the rectal wall in tilted r-DWI, resulting in a higher CNR.

With respect to ADC assessment, no significant difference was found between the mean ADC values of f-DWI with RS-EPI and tilted r-DWI. The above suggested that ADC values measured on tilted r-DWI may be used to predict response to neoadjuvant chemoradiation therapy or as a noninvasive marker of tumor aggressiveness, as the results of previous studies [2–4]. Prior studies have demonstrated that the improved survival rate of rectal cancer was attributed to the application of advanced MRI techniques combined with better preoperative treatment plans [29, 30]. Tilted r-DWI with high image quality may potentially be a promising technique in detecting small lesions and for staging and evaluating the treatment response in patients with rectal cancer. Additionally, multiparametric MRI, including tilted r-DWI, would be expected to provide more information regarding intratumoral components (e.g., bleeding, cystic changes, and necrosis) [27], although further clinical studies will be required to validate these findings.

One disadvantage of reduced field-of-view imaging as used in tilted r-DWI is that the evaluation of potential pelvic abnormalities outside the chosen small FOV is limited. Although f-DWI with RS-EPI which can cover the entire pelvis has the drawback of longer scanning time due to its segmented EPI k-space sampling trajectory compared to SS-EPI [31], f-DWI with RS-EPI can reduce imaging time using its relatively large voxel size, small b-value, and reduced number of excitations, as in the sequence used in this study. A previous study demonstrated that f-DWI with RS-EPI achieved significantly improved lesion conspicuity and overall image quality with fewer artifacts without increasing imaging time, compared to f-DWI with SS-EPI. Therefore, the combined use of tilted r-DWI and f-DWI with RS-EPI sequences can be a reasonable approach for screening of lymph nodes and other pelvic organs.

The present study had several limitations. First, the patient population was small in this retrospective study, which may be prone to selection bias, although this study focused on the image quality of tilted r-DWI compared with f-DWI with RS-EPI for rectal cancer. Thus, large prospective multi-center studies using both 1.5-T and 3.0-T MR system are necessary to elucidate the utility of tilted r-DWI in the preoperative assessment of rectal cancer. Second, the ROIs delineation for measuring SI, SD, and ADC values of the rectal wall and cancer was conducted by a single observer with verification by a second observer, and ROIs were manually drawn, which raises the possibility of sampling errors. Additionally, all the ROI measurements were based on the largest lesion-containing slices, which might not reflect the overall lesion heterogeneity. The entire volume measurement should be considered for further studies [32]. Third, tilted r-DWI and r-DWI without tilted excitation pulses were not compared as r-DWI without tilted excitation pulses was not acquired in this study since it was impractical to add r-DWI without tilted excitation pulses to the clinical protocol in addition to f-DWI and tilted r-DWI. Finally, this study included only patients with untreated rectal cancer. Therefore, the value of tilted r-DWI in predicting the response to neoadjuvant chemoradiation therapy remains to be determined.

In conclusion, tilted r-DWI using 2D selective RF pulses and reduced FOV in the phase-encoding direction provides improved image quality with fewer artifacts and higher rectal lesion conspicuity than f-DWI with RS-EPI, indicating the feasibility of this MR sequence in evaluating rectal cancer in clinical practice.

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Declarations

Conflict of interest Two authors (Thomas Benkert and Hiroshi Imai) were employees of Siemens Healthcare, but the other authors, who are not Siemens Healthcare employees, had control of inclusion of any data and information. Atsuo Inoue, Masahiro Tanabe, Kenichiro Ihara, Keiko Hideura, Mayumi Higashi, Masatoshi Yamane, Takahiro Yamaguchi, Takaaki Ueda, and Katsuyoshi Ito declare they have no financial interests.

Ethical approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Review Board of Yamaguchi University Hospital (September 5, 2022/No 2022–094)."

Consent to participate Written informed consent was waived by the Institutional Review Board.

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