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Technical Feasibility of Quantitative Measurement of Various Degrees of Small Bowel Motility Using Cine Magnetic Resonance Imaging

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Objective: Cine magnetic resonance imaging (MRI) has emerged as a noninvasive method to quantitatively assess bowel motility. However, its accuracy in measuring various degrees of small bowel motility has not been extensively evaluated. We aimed to draw a quantitative small bowel motility score from cine MRI and evaluate its performance in a population with varying degrees of small bowel motility.

Materials and Methods: A total of 174 participants (28.5 ± 7.6 years; 135 males) underwent a 22-second-long cine MRI sequence (2-dimensional balanced turbo-field echo; 0.5 seconds per image) approximately 5 minutes after being intravenously administered 10 mg of scopolamine-N-butyl bromide to deliberately create diverse degrees of small bowel motility. In a manually segmented area of the small bowel, motility was automatically quantified using a nonrigid registration and calculated as a quantitative motility score. The mean value (MV) of motility grades visually assessed by two radiologists was used as a reference standard. The quantitative motility score's correlation (Spearman's ρ) with the reference standard and performance (area under the receiver operating characteristics curve [AUROC], sensitivity, and specificity) for diagnosing adynamic small bowel (MV of 1) were evaluated.

Results: For the MV of the quantitative motility scores at grades 1, 1.5, 2, 2.5, and 3, the mean ± standard deviation values were 0.019 ± 0.003, 0.027 ± 0.010, 0.033 ± 0.008, 0.032 ± 0.009, and 0.043 ± 0.013, respectively. There was a significant positive correlation between the quantitative motility score and the MV (ρ = 0.531, P < 0.001). The AUROC value for diagnosing a MV of 1 (i.e., adynamic small bowel) was 0.953 (95% confidence interval, 0.923–0.984). Moreover, the optimal cutoff for the quantitative motility score was 0.024, with a sensitivity of 100% (15/15) and specificity of 89.9% (143/159).

Conclusion: The quantitative motility score calculated from a cine MRI enables diagnosis of an adynamic small bowel, and potentially discerns various degrees of bowel motility.

Keywords: Cine imaging; Magnetic resonance imaging; Gastrointestinal motility; Small intestine; Bowel

INTRODUCTION

Intestinal dysmotility, which involves impaired contraction or relaxation of the intestinal wall muscles [1-3], is associated with various gastrointestinal disorders, including functional and dysmotility disorders [4-7].

Several conventional techniques have been used to assess small bowel motility, including manometry, hydrogen breath

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tests, plain radiography, small bowel follow-through, and scintigraphy [8-10]. However, they have limited utility because of their poor reliability, lack of standardization, invasiveness, radiation hazards, and the anatomical complexity of the small bowel [11]. In this regard, patients frequently remain undiagnosed or misdiagnosed; moreover, the development of optimal treatments is challenging.

Cine magnetic resonance imaging (MRI), which uses balanced steady-state free precession (bSSFP) pulse sequences, has emerged as a noninvasive method that enables direct visualization and assessment of small bowel motility with good temporal resolution [12-14]. Recently, two groups have independently devised quantitative measurements for evaluating bowel motility on cine MRIs [15-17] using optical flow-based techniques, showing its potential as a reproducible and robust evaluation method for small bowel motility. Using the quantitative measurements of cine MRIs, several studies have revealed less motility of the small bowel in Crohn's disease [18] and chronic intestinal pseudo-obstruction [19] than in healthy controls. Other studies have demonstrated the negative correlations between disease severity and small bowel motility in patients with Crohn's disease [20,21]. However, these studies only focused on the quantitative measurement's clinical utility, and compared the differences in motility between diseased and healthy individuals or between different severities of disease. Its technical feasibility in evaluating various degrees of small bowel motility is yet to be elucidated. Therefore, the accuracy of the quantitative measurement of cine MRI in reflecting various degrees of small bowel motility remains undetermined.

In this regard, our study aimed to draw a quantitative score for small bowel motility using cine MRI and evaluate its feasibility in measuring various degrees of small bowel motility deliberately created by the administration of a small dose of antispasmodic agent as well as in diagnosing different degrees of decreased small bowel motility.

MATERIALS AND METHODS

This study was approved by the institutional review board of the Asan Medical Center (IRB No. 2022-0320), and informed consent was obtained from all the participants.

Study Dataset

During routine magnetic resonance enterography (MRE) practice at the Asan Medical Center, 20 mg of scopolamine-N-butyl bromide (Buscopan; Boehringer Ingelheim) was used as an antispasmodic agent. It was administered twice in split doses of 10 mg for the prevention of motion-related artifacts and worked by suppressing small bowel motility throughout the MRE examination [22-24]. Through this practice, the investigators learned that an initial single 10 mg dose of scopolamine-N-butyl bromide does not produce a full antispasmodic effect and leads to diverse degrees of bowel motility (from no antispasmodic effect at all to a standstill of bowel movement) in patients across a short period of time after administration and when the drug's effects have diminished slightly. Therefore, approximately 5 minutes after intravenously administering the initial 10 mg of scopolamine-N-butyl bromide during the routine MRE acquisition, we intentionally placed a cine MRI acquisition consisting of a single slice of a 22-second-long bSSFP cine MRI and used the bSSFP (2-dimensional balanced turbo-field echo) to obtain a dataset that encompassed a diverse range of bowel motility. A 3-tesla scanner (Philips Healthcare) was used. This single slice was chosen to include the largest area of the small bowel. The temporal resolution was 0.5 seconds per image. Further technical details of the cine MRI protocol are provided in Table 1.

A total of 213 cine MRI series were obtained from 213 participants with suspected Crohn's disease, who were enrolled in our study between November 2020 and July 2021. After reviewing the images, a total of 39 participants were excluded because they failed to hold their breath during image acquisition. Finally, 174 participants were included in the analysis (135 males and 39 females; mean age ± standard deviation [SD], 28.5 ± 7.6 years; Supplementary Table 1). None of the participants presented with any other symptoms after scopolamine-N-butyl bromide administration.

Qualitative Assessment of Small Bowel Motility: Determination of the Reference Standard

Given that the gold standard for bowel motility on cine imaging remains unestablished, the degree of small bowel motility that was qualitatively measured by the readers' visual assessments was used as the reference standard.

Two radiologists independently performed a qualitative assessment of the bowel motility (J.Y.C. and D.W.K. with 1 and 5 years of experience in bowel MRI, respectively). Based on the normal bowel motility observed in all included participants during cine MRI imaging without the administration of scopolamine-N-butyl bromide, the degree of small bowel motility was determined as follows

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Table 1. Cine MRI protocol

Category	Description
Device (magnetic field)	Ingenia, Philips Healthcare (3T)
Preparation	• Fasted for 6 hours • Oral administration of 1 L polyethylene glycol (for 30–40 minutes; 150 mL every 5 minutes) • Intravenous administration of 10 mg scopolamine-N-butyl bromide (approximately 5 minutes before examination)
Parameters	
Echo time, ms	1.0
Repetition time, ms	2.0
Flip angle	45°
Field of view, mm	400 x 400
Slice thickness, mm	8
Spatial resolution, mm	0.9 x 0.9
Acceleration factor for parallel imaging (SENSE)	2.5
Temporal resolution, seconds per image	0.5
Acquisition time, sec	22

MRI = magnetic resonance imaging, SENSE = sensitivity encoding

(Supplementary Video 1): grade 1, adynamic (non-peristaltic) wave; grade 2, decreased but preserved peristalsis; and grade 3, normal peristalsis. Based on the independent results of bowel motility, two different reference standards were established: 1) the mean value (MV) of the grades by the two readers and 2) the consensus grade (CG) after re-evaluation of the discrepant cases.

Quantitative Measurement of the Small Bowel Motility Score

The processes for small bowel segmentation and motility score calculation are described in Figure 1. After a 1-month washout period, one of the radiologists (J.Y.C.) manually drew the small bowel area on the final image of the cine MRI series by using open-source software (ITK-SNAP version 3.6.0., www.itk-snap.org). The drawn areas of the small bowel were automatically applied to the entire time series.

A nonrigid registration was used to quantify small bowel motility [16,17]. With an iterative optical flow method [25-27], it was possible to estimate time-varying displacement fields through the time series of cine MRI. Optical flow calculated a velocity for the points within the images and provided an estimation of where the points would be in the next image sequence. For computing the optical flow, we jointly optimized the two-dimensional displacements and the intensity changes by minimizing the following cost function with respect to u_x, u_y and c [17]:

$$\|(T_{u_x,u_y}\rho + c) - \rho_{ref}\|^2 + R(u_x, u_y, c)$$

where T_{u_x,u_y} is a transformation associated with the displacement fields of u_x and u_y; ρ and ρ_{ref} denote the original and reference images, respectively; and $R(u_x, u_y, c)$ is an additional constraint of regularization term that imposes spatial smoothness on u_x and u_y, and intensity changes on c.

After selecting a reference image that closely represented the median image of the MRI sequence, nonrigid registration was implemented in a multiresolution manner (four scales of 1/8, 1/4, 1/2, and 1). The images were downsampled to each resolution level, and converged displacement fields were interpolated to the finer resolution level using windowed sine interpolation. At each pixel, the SD of the time-varying displacement fields' Jacobian determinant was calculated as the metric for assessing small bowel motility, and the mean of each pixel's metric within the drawn small bowel area was determined as the motility score. All motility score calculations were conducted using MATLAB (R2020b; MathWorks Inc.).

Reproducibility of the Motility Score

To assess the reproducibility of the motility score, the small bowel area of 60 selected participants (i.e., 20 participants randomly selected in each CG) were drawn by a third radiologist (S.H. with 2 years of experience in bowel MRI) in the same manner, i.e., by being blinded to the original results. Motility scores based on the small bowel areas independently obtained from the two different radiologists were compared.

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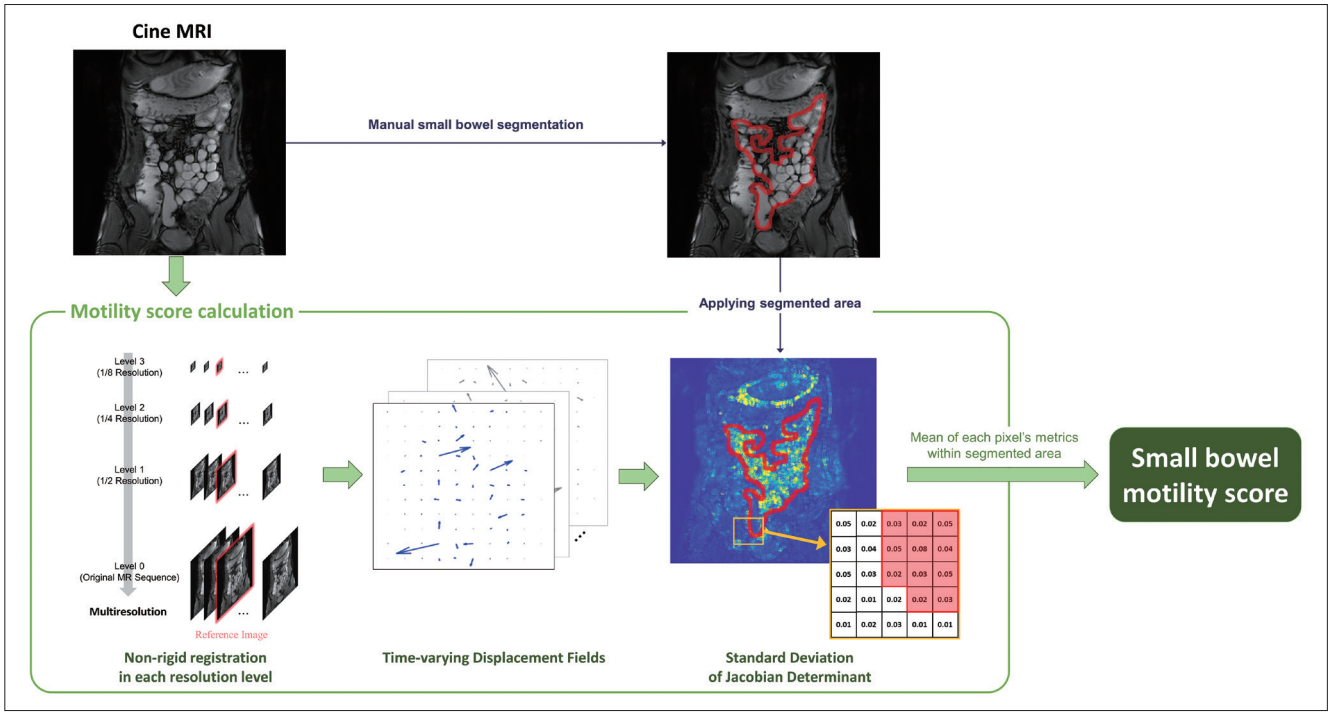

Fig. 1. Overview of the small bowel segmentation and motility score calculation. In a manually segmented area of the small bowel, motility was automatically quantified using a nonrigid registration and calculated as a quantitative motility score. MRI = magnetic resonance imaging, MR = magnetic resonance

Statistical Analysis

The inter-reader agreement was analyzed using weighted kappa (κ) statistics for qualitative assessment (0–0.2, poor agreement; 0.21–0.4, fair agreement; 0.41–0.6, moderate agreement; 0.61–0.8, substantial agreement; and 0.81–1, almost perfect agreement) [28]. The correlation between the motility score and the qualitative grade was calculated with one-way analysis of variance and the Spearman's correlation coefficient (ρ). Reproducibility of the motility score was estimated using the intraclass correlation coefficient (ICC; 0.5–0.75, moderate reproducibility; 0.75–0.9, good reproducibility; > 0.9, excellent reproducibility) from the two-way random model [29]. The receiver operating characteristic (ROC) curves were constructed, and the area under the ROC curve (AUROC) was used to assess the diagnostic performance of the motility score in determining the degree of small bowel motility. The optimal motility score cutoff was estimated using the Youden index, and the corresponding sensitivity and specificity were calculated [30]. All statistical analyses were performed using SPSS version 21.0 (IBM Corp.). *P*-values of < 0.05 were considered as statistically significant.

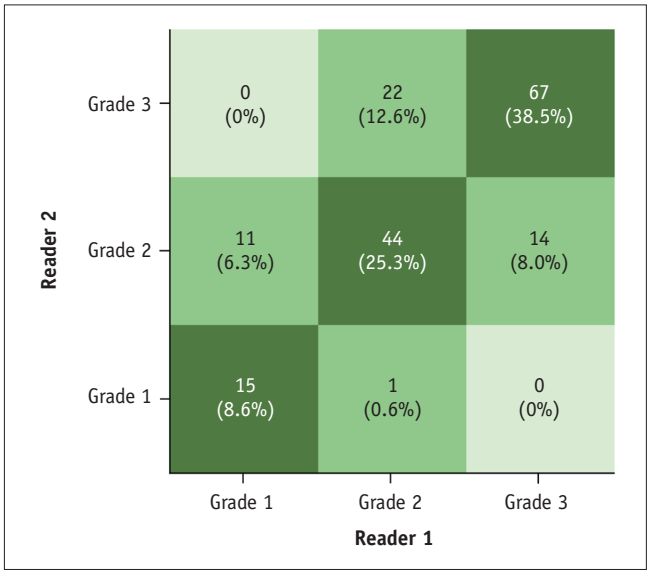

Fig. 2. The confusion matrix regarding the qualitative grade of small bowel motility determined by two independent readers. The darkest green cells denote concordant cases between the two readers. Notably, there is no case with two-grade differences between the two readers (denoted lightest green cells). Grade 1, adynamic (non-peristaltic) wave; grade 2, decreased but preserved peristalsis; and grade 3, normal peristalsis.

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RESULTS

Qualitative Assessment of Bowel Motility and Inter-Reader Agreement

The qualitative visual grades of small bowel motility determined by the two independent readers are summarized in Figure 2. The weighted κ for the inter-reader agreement was 0.61 (95% confidence interval [CI], 0.52–0.71). There were 48 cases (27.6%) where two readers had discordant assessments (grade 1 vs. grade 2, n = 12 [6.9%]; grade 2 vs. grade 3, n = 36 [20.7%]); no cases with two-grade differences between the two readers were found. The MVs were 1 in 15 (8.6%), 1.5 in 12 (6.9%), 2 in 44 (25.3%), 2.5 in 36 (20.7%), and 3 in 67 (38.5%) participants. The CGs were 1 in 22 (12.6%), 2 in 75 (43.1%), and 3 in 77 (44.3%) participants.

Quantitative Bowel Motility Scores

Quantitative bowel motility scores in each participant ranged from 0.012 to 0.093. Based on the MV as the reference standard, the mean ± SD of motility scores was 0.019 ± 0.003 with a MV of 1, 0.027 ± 0.010 with a MV of 1.5, 0.033 ± 0.008 with a MV of 2, 0.032 ± 0.009 with a MV of 2.5, and 0.043 ± 0.013 with a MV of 3 ($P < 0.001$, Fig. 3A). Based on the CG as the reference standard, the mean ± SD of the motility scores was 0.020 ± 0.004 with a CG of 1, 0.032 ± 0.008 with a CG of 2, and 0.042 ± 0.012 with a CG of 3 ($P < 0.001$, Fig. 3B). The quantitative bowel motility score had a positive correlation with the MV ($\rho = 0.531$, $P < 0.001$) and CG ($\rho = 0.607$, $P < 0.001$). Reproducibility of small bowel motility was excellent, with an ICC of 0.987 (95% CI, 0.978–0.992; Supplementary Table 2).

Diagnostic Performance of Quantitative Motility Score

The ROC curves of motility scores to determine the degree of small bowel motility are summarized in Table 2 and Supplementary Figures 1 and 2. For determining the MV of 1, the AUROC was 0.953 (95% CI, 0.923–0.984). The optimal cutoff for the motility score was 0.024, with a sensitivity and specificity of 100% and 89.9%, respectively

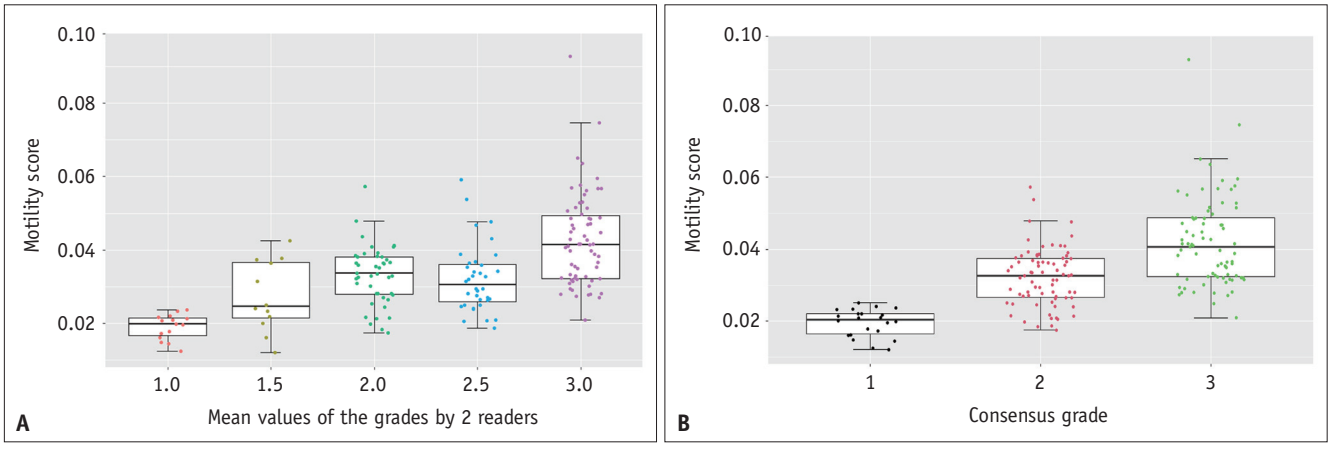

Fig. 3. Scattered box plot of motility scores according to the mean value of grade **(A)** and consensus grade **(B)**. Determined based on the qualitative analyses by two readers using the following criteria: grade 1, adynamic (non-peristaltic) wave; grade 2, decreased but preserved peristalsis; and grade 3, normal peristalsis.

Table 2. Diagnostic performance and cutoff of motility score for determining each grade of small bowel motility

References	Aim	AUROC (95% CI)	Optimal cutoff	Sensitivity	Specificity
Mean values of grades*	1	0.953 (0.923–0.984)	0.024	100% (15/15)	89.9% (143/159)
	≤ 1.5	0.864 (0.779–0.950)	0.025	81.5% (22/27)	89.1% (131/147)
	≤ 2	0.717 (0.641–0.794)	0.025	39.4% (28/71)	93.2% (96/103)
	≤ 2.5	0.783 (0.715–0.852)	0.040	87.9% (94/107)	56.7% (38/67)
Consensus grade*	1	0.962 (0.936–0.988)	0.025	100% (22/22)	89.5% (136/152)
	≤ 2	0.796 (0.732–0.861)	0.039	87.6% (85/97)	55.8% (43/77)

*Determined based on the qualitative analyses performed by two readers using the following criteria: grade 1, adynamic (non-peristaltic) wave; grade 2, decreased but preserved peristalsis; and grade 3, normal peristalsis.
AUROC = area under the receiver operating characteristic curve, CI = confidence interval

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(Supplementary Fig. 1A). The AUROC was relatively lower for determining the MV of ≤ 1.5 (AUROC = 0.864), ≤ 2 (AUROC = 0.717), and ≤ 2.5 (AUROC = 0.783). The sensitivity and specificity were also lower for the MV of ≤ 1.5 (81.5% and 89.1%, respectively, at an optimal cutoff of 0.025), ≤ 2 (39.4% and 93.2%, respectively, at an optimal cutoff of 0.025), and ≤ 2.5 (87.9% and 56.7%, respectively, at an optimal cutoff of 0.040) (Supplementary Fig. 1B-D).

For determining the CG of 1, the AUROC was 0.962 (95% CI, 0.936–0.988). The optimal cutoff of the motility score was 0.025, with a sensitivity and specificity of 100% and 89.5%, respectively (Supplementary Fig. 2A). For determining the CG of ≤ 2, the AUROC (0.796) and sensitivity and specificity (87.6% and 55.8%, respectively) at the optimal cutoff (0.039) were lower (Supplementary Fig. 2B).

DISCUSSION

Using the cine MRI dataset in which a diverse spectrum of small bowel motility was intentionally created by the administration of an antispasmodic agent, our study revealed that the motility scores quantitatively measured by optical flow-based nonrigid registration had a significant positive correlation with the qualitative assessment of the readers (based on the MV as the reference standard, ρ = 0.531 [P < 0.001]; based on CG as the reference standard, ρ = 0.607 [P < 0.001]). For determining an adynamic small bowel (i.e., a MV of 1 and a CG of 1), the optimal cutoffs of the motility score showed perfect sensitivity (100%) and excellent specificity (89.5%–89.9%).

While there is no gold standard for the measurement of bowel motility, manometry has been occasionally used as a comparator for investigating colon motility on cine MRIs [31,32]. However, it is only loosely applicable to small bowel assessment due to its invasiveness and lack of accessibility. Conventional radiologic methods (e.g., plain radiography or small bowel follow-through) are rarely used in clinical practice as they are inaccurate in the evaluation of bowel motility and have radiation hazards [33]. Therefore, we elected a qualitative analysis by the readers (i.e., qualitative grade) as a comparator, because it is the simplest and easiest method in assessing small bowel motility on cine MRIs and has in fact been widely used in previous studies and in clinical practice [34-37]. However, qualitative analysis is subjective, labor intensive, and prone to interobserver variability [34,35,38]. Our study findings are consistent with these reports as results showed a lower margin of substantial inter-reader agreement (weighted κ = 0.61), thereby proving a need for more objective methods for assessing various degrees of small bowel motility using the optical flow-based methods we have investigated in our study.

Our study showed the potential of quantitative motility scores on cine MRI for evaluating different degrees of small bowel motility, in addition to the previous studies, which showed the difference in motility scores according to the presence of intestinal diseases and their severity [18-21]. In particular, our results showed good diagnostic performance for diagnosing an adynamic bowel (AUROC = 0.953 for a MV of 1 and AUROC = 0.962 for a CG of 1). Using the proposed cutoffs (0.024 for a MV of 1 and 0.025 for a CG of 1), all cases of adynamic bowel were detected (sensitivity of 100%), while only a small number of false-positive cases were included (specificity of approximately 90%). However, we reported a lower diagnostic performance (AUROC of 0.717–0.864) to discriminate the intermediate degrees of small bowel motility (i.e., a MV of ≤ 1.5, 2, or 2.5; and a CG of ≤ 2), therefore the quantitative measurement requires further technical improvement. Despite our promising results for diagnosing an adynamic bowel, we admit that the proposed cutoffs would hardly be applied to clinical practice directly (for example, for treatment decisions or monitoring), and further research would be required.

In this study, we also re-confirmed the technique of quantitative motility measurement through cine MRI settings in populations different from that of the two groups that previously devised quantitative motility using the same optical flow-based techniques [15,17]. Nevertheless, we revealed a lack of compatibility, particularly at the different scales of measured motility scores (approximately 0.01–0.1 in our group, vs. 300–2600 in the *Hahnemann* group [21], and 0.05–1 in the *Meny* group [18-20,36,39]). We hypothesize that this was attributed to the difference in the MRI parameters, for example, temporal resolution (0.5 seconds per image in our group vs. 0.57 seconds per image in the *Hahnemann* group and 0.5–1 seconds per image in the *Meny* group). Although our study showed excellent reproducibility of the motility scores when using various segmented small bowel areas, there was a limitation with regards to the technique's application in the external population. Therefore, this warrants the need for standardization of motility scores and cine MRI techniques for generalized implementation of quantitative cine MRI analysis in clinical practice.

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Our study had several limitations. First, the presence of selection bias is a concern as we included only participants with suspected Crohn's disease. Although an association has been reported between the presence of Crohn's disease and the degree of inflammation of the small bowel [18,20,21], it is important to note that our study population did not intend to represent any clinical cohort, such as Crohn's disease, but to deliberately constitute a set of a wide range of bowel motility levels. Therefore, the selection of patients with Crohn's disease is not truly a relevant concern in terms of the study's purpose. Second, the exclusion of cases with respiratory motion artifacts in order to include cine magnetic resonance images appropriate for quantitative analysis, also introduced potential selection bias in the study. Third, it was challenging for readers to categorize the global motility of the segmented small bowel area into a single qualitative grade (i.e., grades 1–3) because each small bowel segment may have had a different degree of small bowel motility (for example, decreased motility in the ileum and normal motility in the jejunum). Likewise, the motility scores solely represented the motility of the whole small bowel area because they were calculated as the mean of each pixel's metric of the segmented small bowel area and did not reflect the value of each bowel segment with different degrees of motility. Lastly, the degree to which the motility score characterizes various motility patterns of the small bowel (e.g., normal vs. abnormal peristalsis) was uncertain and requires further evaluation.

In conclusion, the motility score calculated from cine MRI enables the diagnosis of a adynamic small bowel, and has potential to evaluate different degrees of small bowel motility.

Supplement

The Supplement is available with this article at https://doi.org/10.3348/kjr.2023.0144.

Supplementary Video Legend

Video 1. Qualitative grades of small bowel motility (temporal resolution, 0.5 seconds per image).
Segment 1: Grade 1 = adynamic (non-peristaltic) wave.
Segment 2: Grade 2 = decreased but preserved peristalsis.
Segment 3: Grade 3 = normal peristalsis.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: Ji Young Choi, Jihye Yun, Dong Wook Kim. Data curation: Ji Young Choi, Dong Wook Kim. Formal analysis: Ji Young Choi, Jihye Yun, Subin Heo, Dong Wook Kim. Investigation: Ji Young Choi, Jihye Yun, Subin Heo, Dong Wook Kim. Methodology: Ji Young Choi, Jihye Yun, Subin Heo, Dong Wook Kim. Project administration: Dong Wook Kim. Resources: Dong Wook Kim. Software: Jihye Yun, Dong Wook Kim. Supervision: Dong Wook Kim. Validation: Dong Wook Kim. Visualization: Ji Young Choi, Jihye Yun, Dong Wook Kim. Writing—original draft: Ji Young Choi, Jihye Yun. Writing—review & editing: Subin Heo, Dong Wook Kim, Sang Hyun Choi, Jiyoung Yoon, Kyuwon Kim, Kee Wook Jung, Seung-Jae Myung.

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