Protocol optimization of magnetic resonance colonography for polyp detection using pig colon phantom : Influence of magnetic field strength, colonic distension technique, and MRI sequence

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Directed by Professor Jeong-Sik Yu

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ABSTRACT

Protocol optimization of magnetic resonance colonography for polyp detection using pig colonic phantom : Influence of magnetic field strength, colonic distension technique, and MRI sequence

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Purpose: The aim of this study was to assess the diagnostic performance and image quality of magnetic resonance colonography (MRC) for colon polyp detection using pig colon phantoms and to evaluate the influence of magnetic field strength (1.5 T or 3.0 T), colonic distension technique (bright- or dark-lumen), and MRI sequence.

Materials and Methods: Six pig colon segments (60–92 cm) with 56 artificial colon polyps (0.4–1.6 cm in diameter) were placed in plastic container containing soybean oil. The colon was distended using room air for dark-lumen MRC and with tap water or a gadolinium-chelate based enema fluid for bright-lumen MRC. Each colon phantom was scanned on both 1.5 T and 3.0 T scanners using the following three sequences: axial and coronal two-dimensional (2D) fast imaging with steady-state precession (True-FISP), axial and coronal T2-weighted fat-suppressed (FS) 2D single-shot fast spin echo (SSFSE), and/or axial and coronal T1-weighted FS three-dimensional gradient-echo (3D GRE) sequences. We tried to acquire the highest spatial resolution within a 20-s acquisition time. Two radiologists evaluated the presence of polyps based on a

4-point scale and analyzed image quality with respect to artifacts, colonic wall conspicuity, polyp conspicuity, and polyp contrast using a 5-point scale. Polyp detection sensitivity and image quality were compared between image protocols or sequences using McNemar test, Friedman test, logistic generalized estimating equations, and Wilcoxon signed-rank test.

Result: For polyp detection sensitivity and image quality, MRC obtained at 1.5 T was better than that obtained at 3.0 T, and a bright-lumen technique was superior to a dark-lumen technique. Bright-lumen MRC at 1.5 T was most sensitive for polyp detection ($p < 0.001$) and gave the highest image quality ($p < 0.05$) regardless of polyp size and shape. SSFSE and 3D GRE sequences had highest sensitivity for polyp detection (83.9% and 83.0%, respectively) and image quality for bright-lumen MRC at 1.5 T.

Conclusion: The most effective sequences of MRC for polyp detection were SSFSE- or 3D GRE-based bright-lumen MRC obtained with a 1.5 T scanner. These sequences had the highest polyp detection rate and the best image quality.

Key words: colon, polyp, magnetic resonance imaging, sensitivity, phantom

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I. INTRODUCTION

Colorectal cancer is the third leading cause of cancer and cancer-related death in Korea and the United States and the second leading cause of cancer and cancer-related death in Europe.[1-3] Screening reduces the mortality of colorectal cancer as treatable early-stage cancers or precancerous adenomatous polyps can be detected and removed.[4,5] It is estimated that colonoscopic screening for colorectal cancer can reduce mortality by approximately 50%.[6] Colonoscopy is considered the gold standard colorectal cancer screening test because it can allow detection of polyps and cancers, tissue sampling, and removal of polyps. However, low levels of acceptance in the population due to pain and discomfort associated with the procedure or the pre-procedural bowel cleansing preparation are commonly cited reasons for not undergoing screening colonoscopy.[7]

The search for a more acceptable screening method for colorectal cancer has led to the development of virtual colonoscopy, which includes computed tomography colonography (CTC) and magnetic resonance colonography (MRC).[6] CTC has been proposed as a highly sensitive screening test for the

detection of colonic polyps and cancer.[8-10] The major advantage over optical colonoscopy is that virtual colonography does not require sedation and a cathartic bowel preparation and has a lower risk of procedural complications.[11] CTC has several other advantages such as a short examination time, wide clinical availability, less operator dependency, and lower cost.[6,12] Nevertheless, a major concern associated with CTC is ionizing radiation exposure to healthy individuals, albeit at a low dose.[13,14] Even though previous studies showed that the benefits of screening CTC outweighed the radiation risk,[13,15,16] avoiding ionizing radiation may be the best policy since the radiation risk from repeated radiologic examinations accumulates over a lifetime.[6] In contrast to CTC, MRC is a radiation-free procedure. Moreover, MR imaging provides soft-tissue contrast superior to that obtained with CT. By optimizing the magnetic gradient hardware, coil design, and pulse sequences, MR imaging also reduces acquisition times and improves imaging spatial resolution.[6] These aspects have made an MRC attractive approach for the screening of colorectal neoplasms.[12]

Most colonic loops are collapsed in their physiologic state, so the colon needs to be distended to allow reliable assessment of the bowel wall.[17] MRC should have high contrast between the bowel wall and bowel lumen for reliable visualization of pathology arising from the colonic wall.[17] The contrast mechanism depends on the MRI sequence as well as on the composition of the rectal enema.[6,12,18] There are two primary strategies for MRC: bright-lumen and dark-lumen techniques. Bright-lumen MRC requires a liquid enema consisting of water or water mixed with a gadolinium chelate.[6,12,17,18] Dark-lumen MRC requires filling of the colon with water, room air, or carbon dioxide.[6] T1-weighted (T1w) three-dimensional spoiled gradient-echo (3D GRE), true fast imaging with steady-state precession (True-FISP), and T2-weighted (T2w) single-shot fast spin echo (SSFSE) sequences have generally been used. Most early reports of MRC used the bright-lumen technique and a 1.5 T scanner.[19-21] 3.0 T scanners have since become commercially available and have been increasingly used for MRC,[18,22,23] and most recent studies have used the dark-lumen technique.[22-27] To

our knowledge, these changes were not substantiated by scientific research on colonic lesion detection and image quality but were motivated by other reasons, such as cost and patient acceptance.[20,28]

Therefore, we aimed to comprehensively assess the influence of magnetic field strength, colonic distension technique, and MRI sequence for colon polyp detection sensitivity and image quality of MRC using an anthropomorphic colon phantom. The purpose of this study was to evaluate the diagnostic performance and image quality of MRC and to determine the optimal protocol with consideration of these factors or techniques.

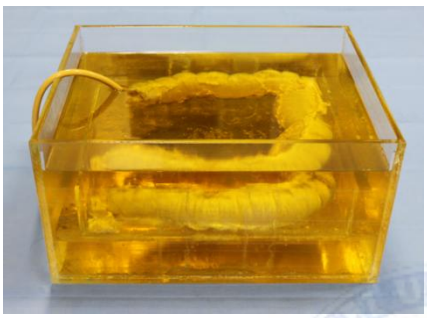
II. MATERIALS AND METHODS

1. Colon Phantom Preparation

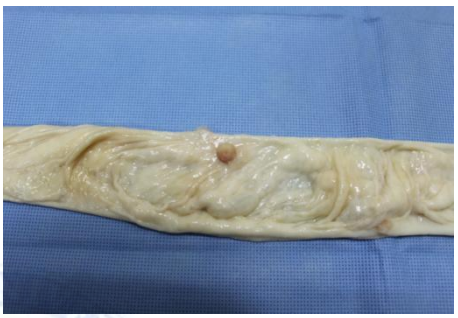
Six phantom colonic segments of 60–92 cm were prepared using pig colons obtained from an abattoir. A researcher created 56 polyps using lymph node tissue and raw lean sirloin steak from pigs. Ten polyps were flat and 46 were sessile (Fig. 1). The height of the flat polyps did not exceed 3 mm.[12,29] The diameter of the polyp was measured with a caliper and a millimeter-marked ruler. Fifteen polyps were 4 mm in diameter, 10 were 0.6 mm, 14 were 0.8 mm, 10 were 1.0 mm, 2 were 1.2 mm, 3 were 1.4 mm, and 2 were 1.6 mm. The colonic segments were inverted and polyps were attached with cyanoacrylate glue to the inner surface of the pig colon. The researcher recorded the size, shape, and location of the polyps. The colon was then reinverted taking care not to detach the polyps from the colon. One end of the colonic segment was tied with cable ties. A 24-F Foley catheter was inserted into the open end of the segment and the balloon was inflated. The open end was then closed with cable ties.

The colon specimen was placed in a 38 × 30 × 20 cm plastic container

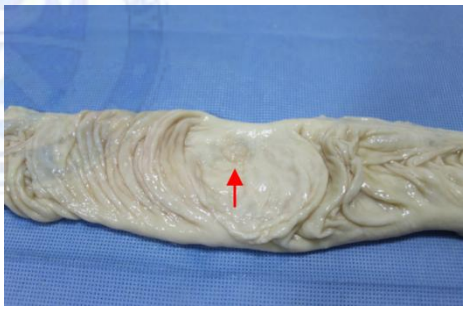
containing 18 mL of soybean oil to simulate visceral fat.[30] Before MR scanning, the colonic segments were distended using room air, tap water, or gadolinium mixture-based enema fluid for dark-lumen or bright-lumen MRC. Each colon phantom was scanned on both 1.5 T and 3.0 T MR scanners. After MR scanning, the researcher dissected the colon phantoms and reconfirmed the size and location of the polyps.



(a) Pig colon phantom



(b) A sessile polyp



(c) A flat polyp

Figure 1. Pig colon phantom with sessile and flat polyps. (a) Pig colonic segment in plastic container filled with soybean oil. (b) A sessile polyp attached to the inner surface of the pig colon. (c) A flat polyp (arrow) attached to the inner surface of the pig colon.

2. MRI Sequences

MRI examinations were performed on both a 1.5 T scanner (Magnetom Avanto, a TIM system; Siemens Medical Solutions, Erlangen, Germany) using 12-channel body and spine matrix coils, and on a 3.0 T scanner (Achieva 3.0 T-TX, Philips Healthcare, Best, Netherlands) using a 32-channel SENSE Torso/cardiac coil. The sequence protocols consisted of two-dimensional (2D) axial and coronal True-FISP, axial and coronal T2w fat-suppressed (FS) 2D SSFSE, and T1w FS 3D GRE sequences. The imaging parameters for the sequences are shown in Table 1. We tried to obtain spatial resolution and signal-to-noise ratio (SNR) as high as possible for each sequence within an acquisition time of 20 seconds or less. Only axial SSFSE was obtained twice with an acquisition time of 40 seconds (2 × 20 seconds).

The colonic segment needed to be distended to allow a reliable assessment of the bowel wall. Therefore, using a rectal enema consisting of room air, tap water, and gadolinium-chelate based enema fluid, each phantom was performed both dark-lumen and bright-lumen MRC. First, air was introduced into the colonic segment until it was distended to the maximal expected diameter of the colon for dark-lumen MRC. True-FISP, SSFSE, and 3D GRE were obtained for dark-lumen MRC. Second, after extracting intraluminal air, a 1.5-2 L volume of tap water was instilled into the colon with 150 cm of hydrostatic pressure and True-FISP and SSFSE were performed for bright-lumen MRC. Finally, after evacuation of intraluminal water, the colonic segment was filled with a 1.5-2 L volume of gadolinium chelate (Gd-DTPA, BONO-I; Central Medical Service, Seoul, Korea)-based enema fluid (10 mmol/L or 1:100). Then, 3D GRE was obtained for bright-lumen MRC (Fig. 2).

Table 1. Acquisition parameters of two-dimensional true fast imaging with steady-state precession (True-FISP), T2-weighted two-dimensional single-shot fast spin echo (SSFSE), and T1-weighted three-dimensional gradient-echo (3D GRE) sequences for MR colonography with 1.5 T and 3.0 T MRI scanners.

		1.5 T						3.0 T					
		True-FISP		SSFSE		3D GRE		True-FISP		SSFSE		3D GRE	
		Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial	Coronal	Axial
TR	ms	4.72	4.25	800	730	3.02	4.74	5.5	4	659	474	5.2	4.7
TE	ms	2.36	2.13	84	82	0.98	2.38	2.8	1.99	80	80	2.5	2.2
Flip angle	°	60	60	150	150	20	20	40	40	90	90	20	20
Field of view		320 x 280	320 x 180	320 x 280	320 x 187	320 x 280	373 x 187	320 x 281	300 x 180	320 x 279	300 x 180	320 x 284	300 x 179
Matrix		256 x 188	192 x 92	256 x 224	192 x 112	320 x 280	320 x 144	132 x 116	100 x 60	124 x 106	100 x 58	212 x 189	168 x 89
Slice thickness	mm	3.0	5.0	3.0	5.0	3.0	3.0	3.0	5.0	3.0	4.0	3.0	3.0
No. of Slice		28	57	25	55	30	104	28	67	28	78	30	106
Voxel size (aquired)	mm	1.5 x 1.3 x 3.0	2.0 x 1.7 x 5.0	1.3 x 1.3 x 3.0	1.7 x 1.7 x 5.0	1.0 x 1.0 x 3.0	1.3 x 1.2 x 3.0	2.4 x 2.4 x 3.0	3.0 x 3.0 x 5.0	2.6 x 2.6 x 3.0	3.0 x 3.1 x 4.0	1.5 x 1.5 x 6.0	1.8 x 1.1 x 6.0
Voxel size (recon)	mm							0.6 x 0.6 x 3.0	0.8 x 0.8 x 5.0	0.6 x 0.6 x 3.0	0.8 x 0.8 x 4.0	0.4 x 0.4 x 3.0	0.5 x 0.5 x 3.0
NEX		1	1	1	1	1	1	2	2	2	2	1	1
Parallel factor		2	2	2	2	2	2	3	3	3	3	1.5 x 1.5	1.5 x 1.5
Bandwidth	Hz/Px	416	395	465	465	600	400	463.5	500	600.5	558.2	288.6	342.1
Fat saturation		-	-	O	O	O	O	-	-	O	O	O	O
Acquition time	s	20	21	20	40	15	19	20	20	20	37	17	19

TR: repetition time, TE: echo time, NEX: number of excitations

3. Data analysis

Two radiologists with 14 years and 5 years of experience reading MR enterography and CTC independently evaluated the images of MRC in a random fashion using a picture archive and communication systems workstation (Centricity RA1000, GE Healthcare, Milwaukee, WI, USA). The radiologists were blinded to the magnetic strength of MRI, colonic distension technique, and MRI sequence as well as to the location and size of the polyps.

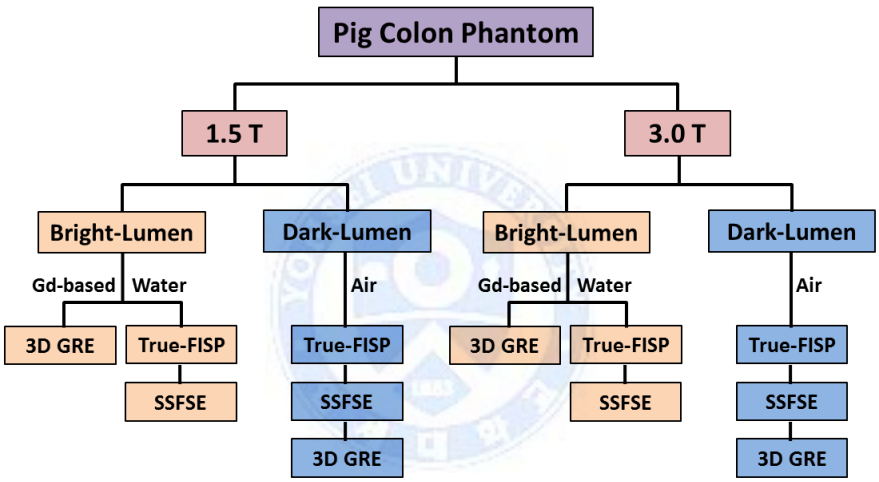


Figure 2. Study flow chart of MR colonography using pig colon phantoms, considering the magnetic strength of MRI, bright-lumen and dark-lumen techniques, and MRI sequences.

The radiologists recorded the presence and location of polyps visualized on each image based on the following 4-point scale: 1 = definitely absent (no identifiable lesion), 2 = probably absent (questionable), 3 = probably present, 4 = definitely present. Confidence scores of 1 and 2 were regarded as negative for the presence of a polyp, whereas confidence scores of 3 and 4 were considered positive for the presence of a polyp. Sensitivities of detection of the polyps were calculated according to magnetic strength, colonic distension technique,

sequences, polyp size, and polyp shape (sessile or flat). With respect to size, colorectal polyps are generally categorized as small (≤ 5 mm), intermediate (6–9 mm), and large (≥ 10 mm).[12,22,25,31] Small polyps have a low risk of advanced disease (0.5%) and intermediate polyps exhibit a slightly higher risk (1.5%), whereas large polyps exhibit an overall 15% risk of advanced disease.[32] Therefore, polyps in the present study were also classified according to this size category. The radiologists subjectively scored the image quality parameters of presence of artifacts, bowel wall conspicuity, polyp conspicuity, and polyp contrast to colon luminal signal intensity using a 5-point scale (1 = poor/non-diagnostic, 2 = fair/substandard, 3 = good/standard image quality, 4 = very good/better than standard, 5 = excellent).

4. Statistics

All statistical analyses were performed using IBM SPSS Statistics 21.0 for Windows (IBM Corporation, Somers, NY, USA) and SAS (version 9.2; SAS Institute, Cary, NC, USA). The McNemar test and Mann-Whitney U test were used to compare detection sensitivity of two image groups. For comparing multiple image groups, the logistic generalized estimating equations (GEE) test was used first. If the logistic GEE test yielded $p < 0.05$, McNemar test with Bonferroni correction was used for pairwise group comparison. The Wilcoxon signed-rank test and Mann-Whitney U test were used to compare image quality of two image groups. The Friedman test was first used for comparison image quality of multiple groups. If the Friedman test yielded $p < 0.05$, Wilcoxon signed-rank test with Bonferroni correction was used for pairwise group comparison. Differences were considered significant when the p value was less than 0.05. Bonferroni correction for multiple comparisons was applied to assess possible significance with p value of $< 0.05 \times 2/n(n-1)$, where n = the number of groups. The linear-weighted kappa statistic was used to assess interobserver agreement in scoring and was interpreted using the guidelines of Landis and Koch.[33]

III. RESULTS

1. Sensitivity of polyp detection

MRC obtained on the 1.5 T MR scanner had significantly higher detection sensitivity than that obtained at 3.0 T ($p < 0.001$), regardless of polyp size or polyp shape (Fig. 3). Sessile polyps showed significantly higher sensitivity than flat polyps in both 1.5 T and 3.0 T images ($p < 0.001$). In comparisons of polyp detection sensitivity between bright-lumen and dark-lumen techniques, bright-lumen MRC was significantly superior to dark-lumen MRC ($p < 0.001$), regardless of polyp size or polyp shape (Fig. 4). Sessile polyps had significantly higher sensitivity than flat polyps in both bright-lumen and dark-lumen techniques ($p < 0.001$).

Considering both magnetic field strength and colonic distension technique, bright-lumen MRC obtained on the 1.5 T scanner was most sensitive for polyp detection, followed by bright-lumen MRC at 3.0 T, dark-lumen MRC at 1.5 T, and dark-lumen MRC at 3.0 T (Fig. 5 and 6). The difference between these protocols was statistically significant ($p < 0.008$ [$= 0.05/6$]) for all polyps and large- or intermediate-size polyps. For small polyps (Fig. 5a) and flat polyps (Fig. 5b), there was no significant difference in polyp detection sensitivity between bright-lumen MRC at 3.0 T and dark-lumen MRC at 1.5 T and between dark-lumen MRC at 1.5 T and dark-lumen MRC at 3.0 T. Sessile polyps had significantly higher sensitivity than flat polyps in each MRC protocol ($p < 0.05$).

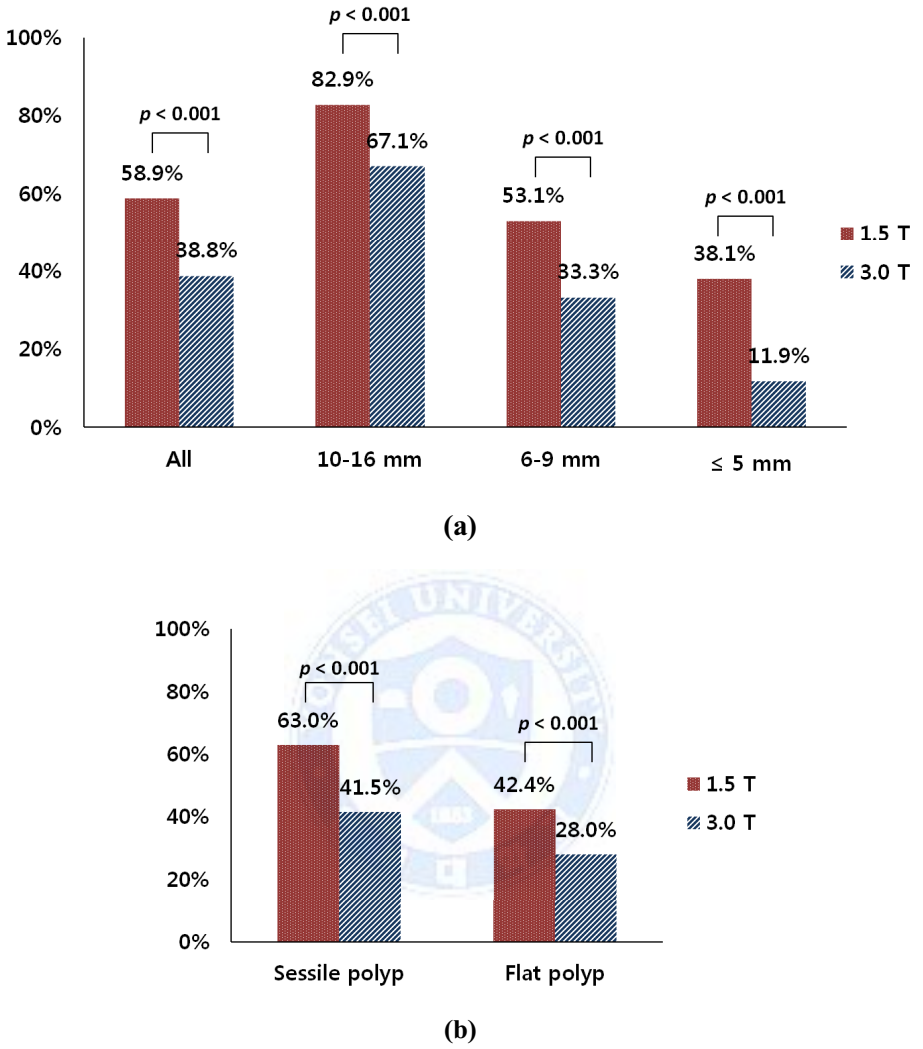
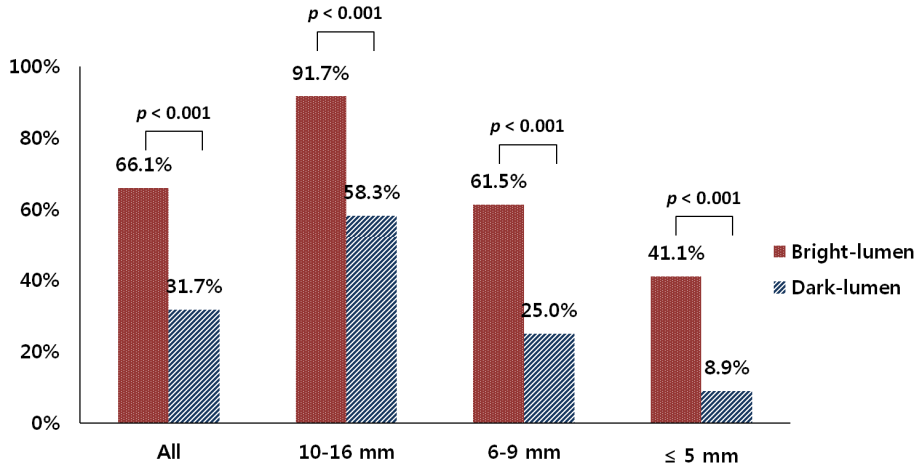
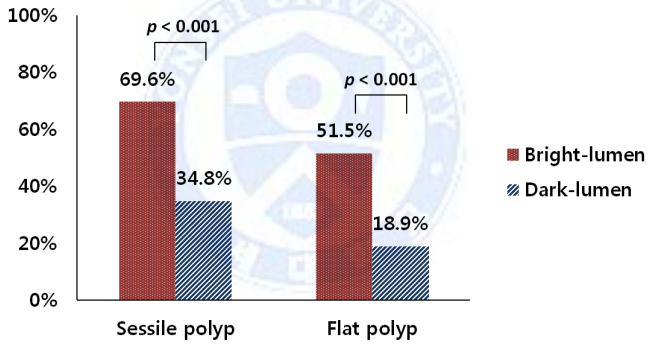


Figure 3. Polyp detection sensitivity of MR colonography (MRC) performed on 1.5 T and 3.0 T scanners. The polyp detection sensitivity of MRC obtained at 1.5 T is significantly higher than that at 3.0 T, regardless of polyp size (a) and polyp shape (b).



(a)



(b)

Figure 4. Comparison of polyp detection sensitivity between bright-lumen and dark-lumen techniques. Bright-lumen MR colonography (MRC) has significantly higher polyp detection sensitivity than dark-lumen MRC, regardless of polyp size (a) and polyp shape (b).

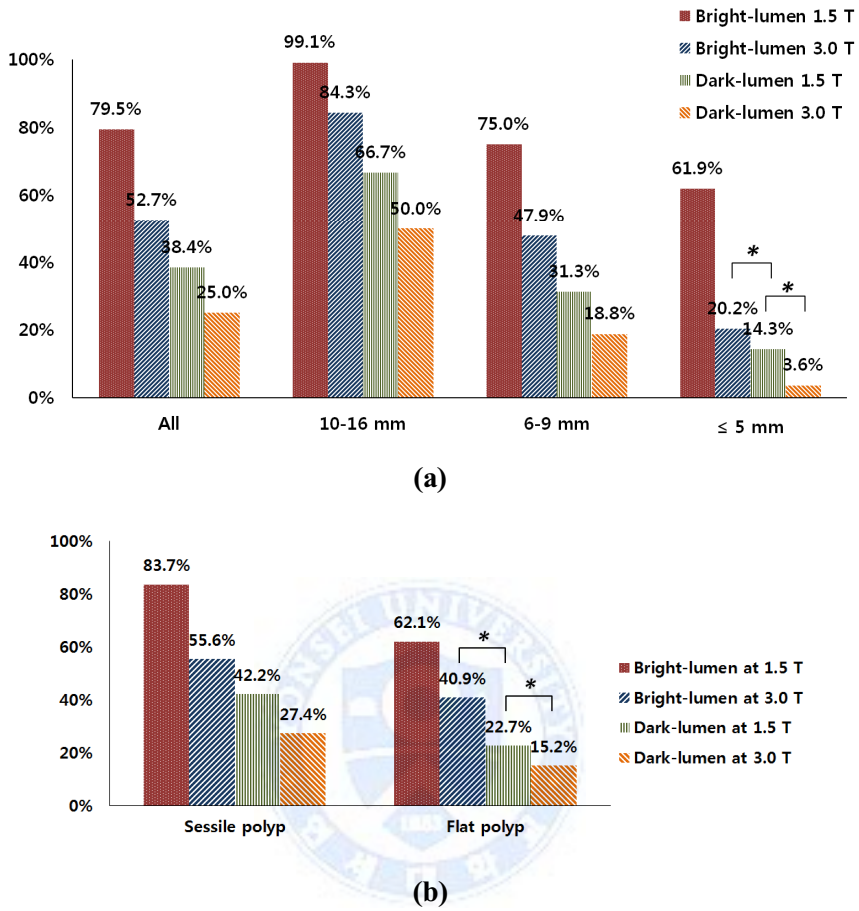
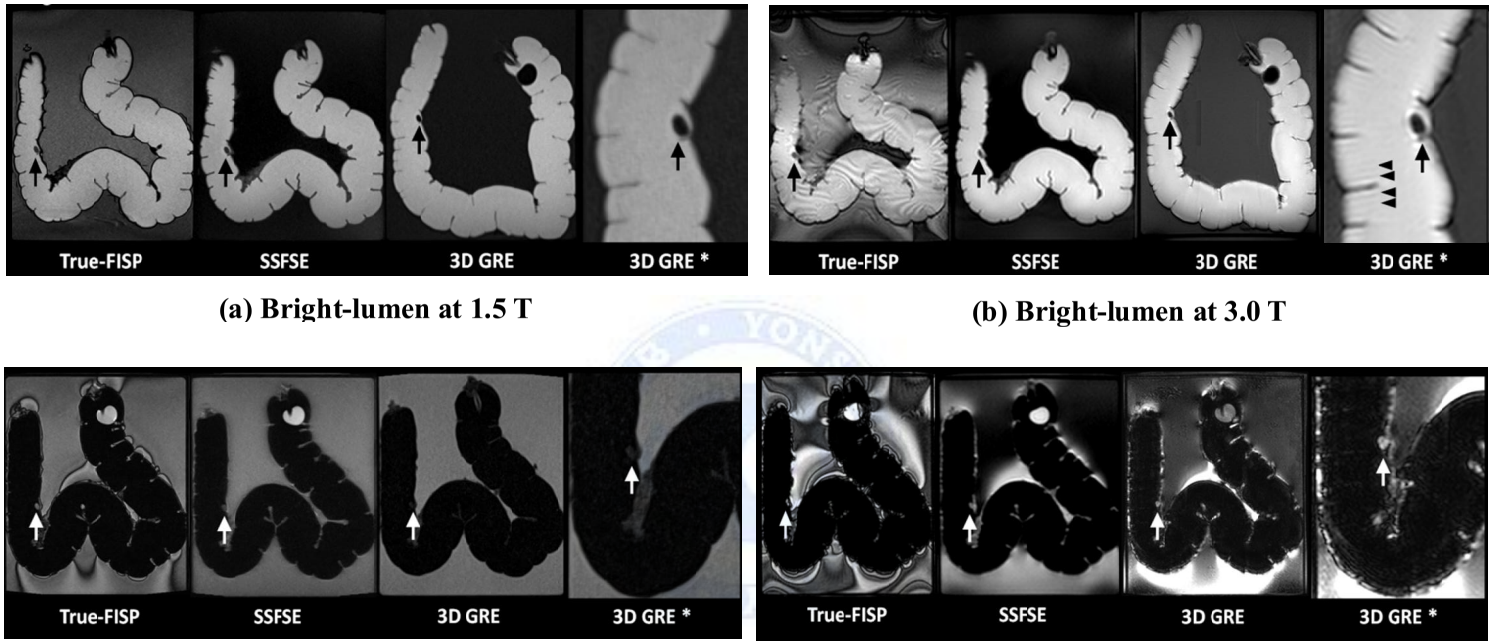


Figure 5. Polyp detection sensitivity of bright-lumen and dark-lumen MR colonography (MRC) obtained with 1.5 T and 3.0 T MR scanners, according to polyp size (a) and polyp shape (b). The sensitivity of the MRC protocols in descending order is as follows: bright-lumen MRC obtained with 1.5 T scanner (Bright-lumen at 1.5 T), bright-lumen MRC at 3.0 T, dark-lumen MRC at 1.5 T, and dark-lumen MRC at 3.0 T. Pairwise group comparisons among the four protocols show significant differences ($p < 0.008$) for all polyps, large-size (≥ 10 mm) or intermediate-size (6–9 mm) polyps, and sessile-shape polyps. For small polyps (≤ 5 mm) (a) and flat polyps (b), dark-lumen MRC at 1.5 T has no difference in sensitivity compared to bright-lumen at 3.0 T or dark-lumen at 3.0 T (*, $p > 0.008$ [= 0.05/6]).



(a) Bright-lumen at 1.5 T **(b) Bright-lumen at 3.0 T**

(c) Dark-lumen at 1.5 T **(d) Dark-lumen at 3.0 T**

Figure 6. An 8 mm-size sessile polyp (arrow) in MR colonography (MRC). (a) Bright-lumen MRC obtained at 1.5 T scanner. (b) Bright-lumen MRC obtained at 3.0 T scanner. Blurring artifact was noted (arrow head). (c) Dark-lumen MRC obtained at 1.5 T scanner. (d) Dark-lumen MRC obtained at 3.0 T scanner. True-FISP = two-dimensional fast imaging with steady-state precession, SSFSE = fat-suppressed two-dimensional single-shot fast spin echo, 3D GRE = fat-suppressed three-dimensional gradient-echo, 3D GRE* = partial magnification image of 3D GRE.

All sequences of bright-lumen MRC performed on the 1.5 T scanner had a higher sensitivity for polyp detection compared to the sequences of other protocols (Fig. 7). SSFSE or 3D GRE generally had higher sensitivity than True-FISP for all MRC protocols. In bright-lumen MRC at 1.5 T, SSFSE had higher sensitivity than True-FISP ($p = 0.004$) and no difference in sensitivity compared to 3D GRE ($p = 0.999$). In the bright-lumen technique at 3.0 T, both SSFSE and 3D GRE had superior sensitivity than True-FISP ($p < 0.001$). There was no difference in polyp detection sensitivity among three sequences of dark-lumen MRC at both 1.5 T and 3.0 T, except that 3D GRE had higher sensitivity than True-FISP at 3.0 T ($p < 0.001$). The sensitivities of all sequences of dark-lumen MRC were less than 50%. Sensitivity for sessile polyps was generally higher than that for all polyps for all sequences of all MRC protocols. 3D GRE of bright-lumen MRC obtained at 1.5 T had sensitivity of 90% for sessile polyps with 4–16 mm in diameter, which was the highest sensitivity obtained in the present study. Detection sensitivity for flat polyps was 55–68% for bright-lumen MRC at 1.5 T, and the other MRC protocols had sensitivity less than 50%. There was no significant difference in detection sensitivity for flat polyps among the three sequences for all four protocols ($p > 0.05$).

Table 2 shows the sensitivity for polyp detection of MRC by two readers according to magnetic field strength of MRI scanner, colonic lumen distention technique, MRI sequence, and polyp size. In bright-lumen MRC performed at 1.5 T, all large polyps (10–16 mm in diameter) were detected, except for one 10-mm polyp in the 3D GRE sequence observed by reader 2. Both readers detected 66.7–87.5% of intermediate size polyps (6–9 mm) and 57.1-85.7% of small polyps (≤ 5 mm) on SSFSE and 3D GRE sequences. In addition, 88.9–100% of large polyps and 33.3–75% of intermediate size polyps were correctly identified with SSFSE or 3D GRE sequence of bright-lumen MRC at 3.0 T. In dark-lumen MRC at 1.5 T or 3.0 T, the detection sensitivity for intermediate size polyps (6–9 mm) was less than 50%.

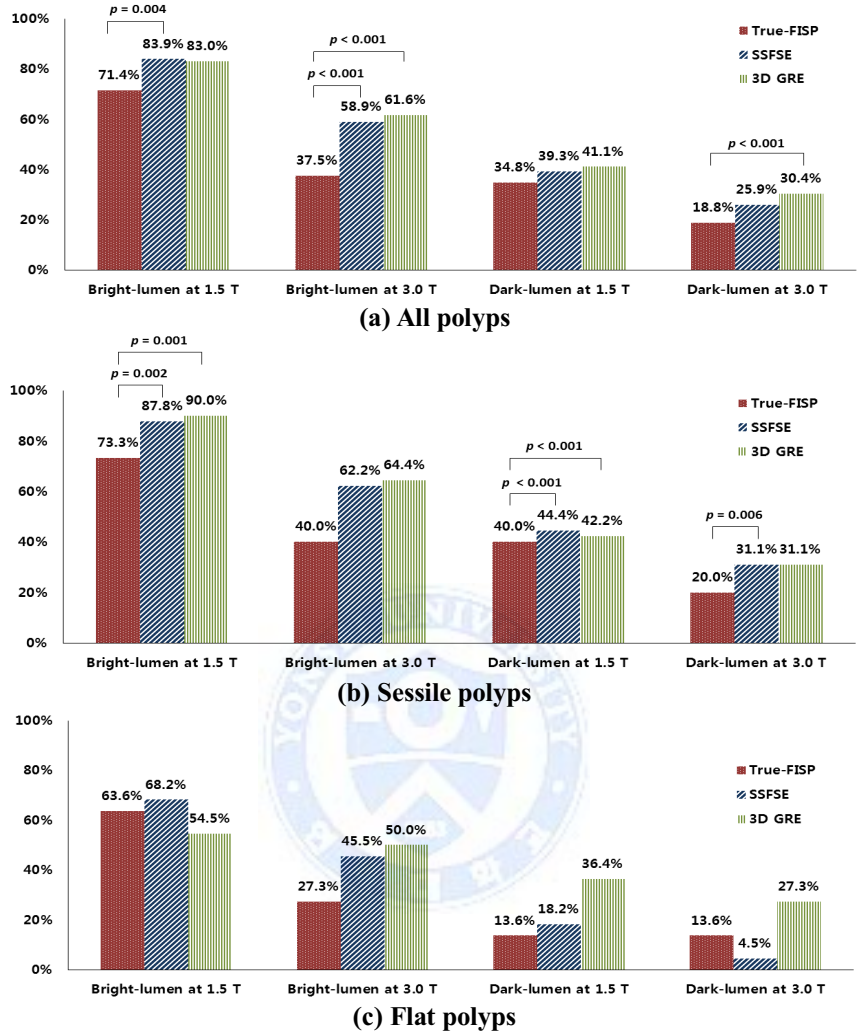


Figure 7. The sensitivity of polyp detection at each sequence of MR colonography protocols for all of polyps (a), sessile polyps (b) and flat polyps (c). Both single-shot fast spin echo (SSFSE) and three-dimensional gradient-echo (3D GRE) have generally higher sensitivity than fast imaging with steady-state precession (True-FISP) for all of polyps and sessile polyps. Especially, SSFSE and 3D GRE at bright-lumen technique performed on 1.5 T (Bright-lumen at 1.5 T) had highest sensitivities, compared to the sequences of other protocols. For flat polyps, there was no significant difference in sensitivity among three sequences at all four protocols ($p > 0.05$). P value of > 0.017 ($= 0.05/3$) is not given in figure.

Table 2. Sensitivity of polyp detection by two readers according to magnetic field strength of MRI, colonic distension technique, MRI sequence, and polyp size.

		Reader 1				Reader 2			
		1.5 T		3.0 T		1.5 T		3.0 T	
		Bright-lumen	Dark-lumen	Bright-lumen	Dark-lumen	Bright-lumen	Dark-lumen	Bright-lumen	Dark-lumen
True-FISP	10-16 mm (n =18)	100%	77.8%	72.2%	38.9%	100%	61.1%	50.0%	27.8%
	6-9 mm (n=24)	79.2%	37.5%	45.8%	25.0%	62.5%	16.7%	29.2%	12.5%
	≤ 5mm (n=14)	50.0%	0.0%	14.3%	0.0%	21.4%	7.1%	0.0%	0.0%
	Total (n=56)	78.6%	41.1%	46.4%	23.2%	64.3%	28.6%	28.6%	14.3%
SSFSE	10-16 mm (n =18)	100%	77.8%	100%	66.7%	100%	66.7%	94.4%	50.0%
	6-9 mm (n=24)	87.5%	29.2%	58.3%	16.7%	75.0%	33.3%	33.3%	12.5%
	≤ 5mm (n=14)	78.6%	7.1%	42.9%	7.1%	57.1%	14.3%	21.4%	0.0%
	Total (n=56)	89.3%	39.3%	67.9%	30.4%	78.6%	39.3%	50.0%	21.4%
3D GRE	10-16 mm (n =18)	100%	72.2%	100%	55.6%	94.4%	44.4%	88.9%	55.6%
	6-9 mm (n=24)	79.2%	41.7%	75.0%	20.8%	66.7%	29.2%	45.8%	20.8%
	≤ 5mm (n=14)	85.7%	28.6%	35.7%	0.0%	78.6%	28.6%	7.1%	0.0%
	Total (n=56)	87.5%	48.2%	73.2%	26.8%	8.6%	33.9%	50.0%	26.8%

True-FISP: two-dimensional fast imaging with steady-state precession, SSFSE: T2-weighted fat-suppressed two-dimensional single-shot fast spin echo, 3D GRE: T1-weighted fat-suppressed three-dimensional gradient-echo.

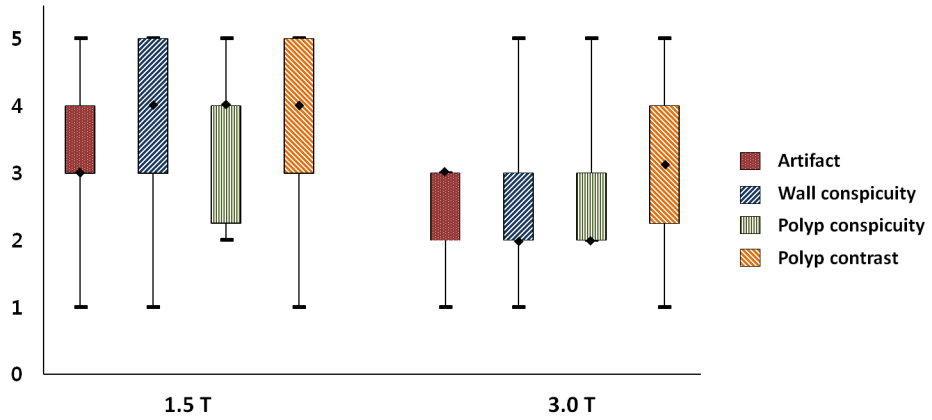
2. Image quality

MRC obtained with the 1.5 T scanner had better image quality than that obtained with the 3.0 T scanner with respect to artifacts, colon wall conspicuity, polyp conspicuity, and polyp contrast (Fig. 8a). Overall image quality of bright-lumen MRC was significantly superior to that of dark-lumen MRC (Fig. 8b). On both 1.5 T and 3.0 T scanners, the image quality of bright-lumen MRC had higher scores than dark-lumen MRC ($p < 0.006$) (Fig. 9). Bright-lumen MRC at 1.5 T had the highest image quality scores and dark-lumen MRC at 3.0 T had the lowest mean image quality scores.

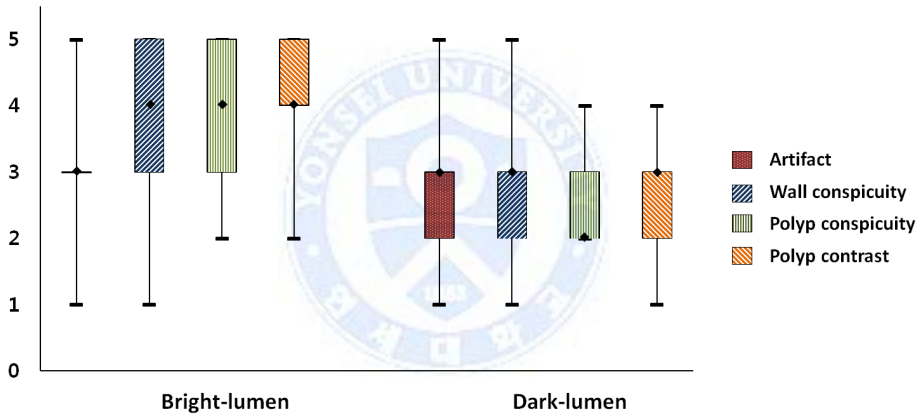
In bright-lumen MRC at 1.5 T, True-FISP, SSFSE, and 3D GRE had no significantly difference in image quality, except for wall conspicuity between SSFSE and 3D GRE (Fig. 10a). Artifacts of True-FISP sequence were significantly inferior to those of SSFSE and 3D GRE sequences at all MRC protocols, except for bright-lumen technique obtained at 1.5 T (Fig. 10). 3.0 T has a 2-fold increase in SNR, which allows improve spatial resolution.[18,34] Contrary to expectations, however, scores of wall conspicuity and polyp conspicuity of 3D GRE sequence at 3.0 T were significantly lower than those at 1.5 T ($p < 0.05$), on both bright- and dark-lumen techniques (Fig. 9 and 10).

3. Interobserver agreement

Interobserver agreement was substantial (kappa = 0.645) for polyp detection and moderate (kappa = 0.576) for image quality analysis.



(a)



(b)

Figure 8. Comparison of artifacts, colon wall conspicuity, polyp conspicuity, and polyp contrast of MR colonography (MRC) obtained at 1.5 T and 3.0 T (a) and using bright-lumen and dark-lumen techniques (b). Box-and-whisker plots show median (center of diamond), quartiles (top and bottom lines of each box), and upper and lower adjacent (top and bottom lines) values of the subjective scores. MRC performed on a 1.5 T scanner has significantly higher image quality scores than that performed on a 3.0 T scanner ($p \leq 0.002$), and the bright-lumen technique has superior image quality compared with the dark-lumen technique ($p < 0.001$).

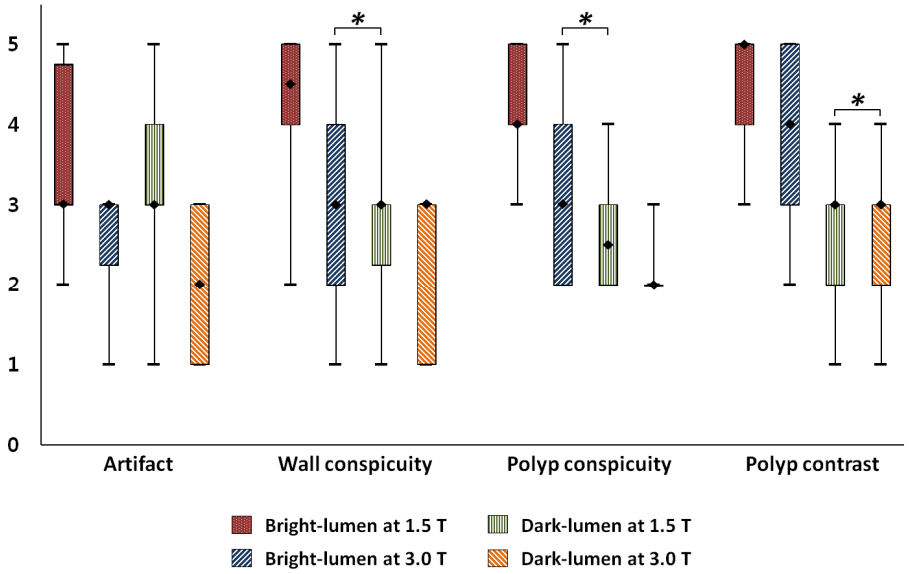
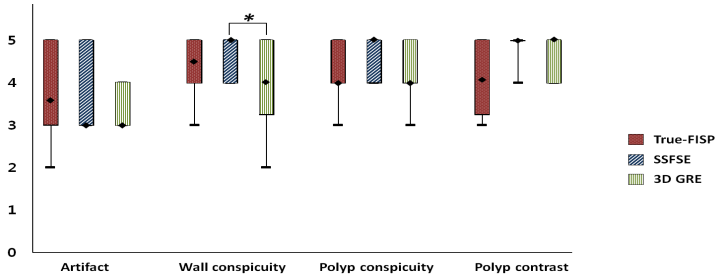
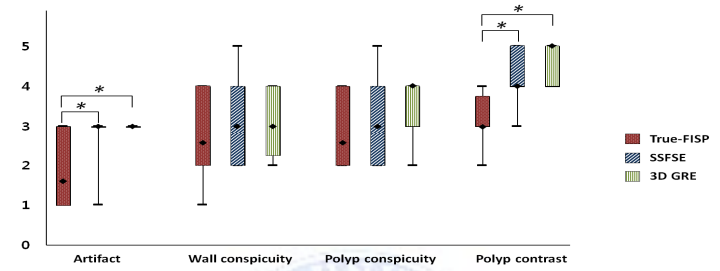


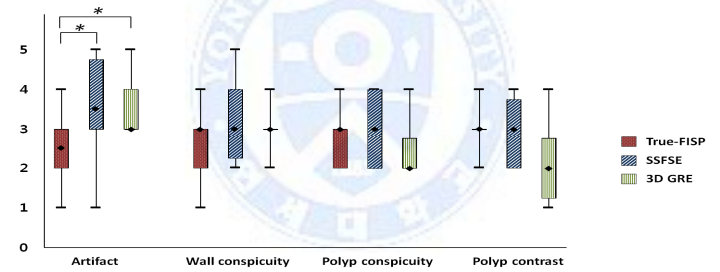
Figure 9. Artifact, colon wall conspicuity, polyp conspicuity, and polyp contrast of bright-lumen and dark-lumen MR colonography (MRC) obtained at both 1.5 T and 3.0 T MR scanners. Bright-lumen MRC at 1.5 T had highest image quality scores and dark-lumen MRC at 3.0 T had lowest image quality scores. * means that there was no significant diffence in score comparison ($p > 0.008 = 0.05/6$).



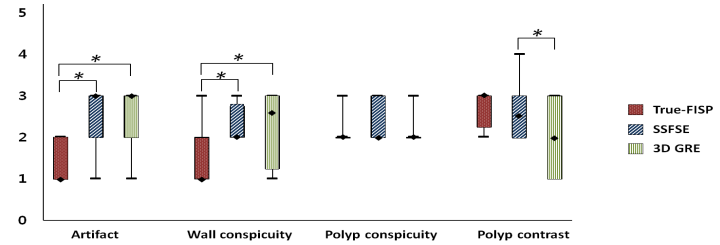
(a) Bright-lumen MR colonography at 1.5 T



(b) Bright-lumen MR colonography at 3.0 T



(c) Dark-lumen MR colonography at 1.5 T



(d) Dark-lumen MR colonography at 3.0 T

Figure 10. Image quality at each sequence of four MR colonography protocols. * means that there was a significant diffence in score comparison (p value < 0.017 = 0.05/3).

IV. DISCUSSION

Findings of this study showed that MRC obtained on a 1.5 T scanner was superior to that obtained at 3.0 T, and that the bright-lumen technique was better than the dark-lumen technique, with respect to polyp detection and image quality. As a consequence, bright-lumen MRC acquired at 1.5 T was the best protocol. In particular, a water enema-based SSFSE sequence and gadolinium mixture enema-based 3D GRE sequence provided the greatest polyp detection rate and the best image quality.

MRC is based on the principles of ultra-fast imaging. Each sequence has to be acquired under breath-hold condition, so an appropriate hardware system is needed. In the past MRC was mostly performed using 1.5 T scanners, although recent studies have proven the feasibility of MRC on 3.0 T systems.[17,35,36] The 3.0 T scanner yields double the SNR, which may improve spatial resolution and reduce acquisition time.[18,34] Therefore, 3.0 T was expected to have a superior polyp detection rate and to improve image quality.[6] However, some studies showed no significant difference in polyp detection or image quality between 1.5 T and 3.0 T for 3D GRE or SSFSE sequences.[35,36] Moreover, susceptibility artifacts are greater at 3.0 T and may reduce the image quality and polyp detection rate.[6,18] In particular, True-FISP and 3D GRE have a high affinity for susceptibility artifacts on air-based dark-lumen MRC, thus exaggerating the artifacts produced by a higher magnetic field strength.[6,18] In the present study, 1.5 T had better image quality and polyp detection sensitivity than 3.0 T. A previous study using a phantom showed no significant difference in the detection of colonic polyps 6 mm or larger between 1.5 T and 3.0 T.[36] In that study, overall sensitivity for polyp detection was 56% at 1.5 T and 55% with 3.0 T MR imaging.[36] Another study reported conflicting results, showing that dark-lumen MRC performed at 3.0 T had a sensitivity of 100% for all colon cancers and polyps larger than 6 mm in 34 patients.[23] Yet another study reported better image quality at 1.5 T, compared to 3.0 T MR imaging.[35]

In MRC, the bright-lumen or dark-lumen strategy refers to the signal intensity of the bowel lumen. High contrast between the bowel wall and bowel lumen is crucial for reliable visualization of pathology arising from the colonic wall.[17] Bright-lumen MRC requires a liquid enema consisting of water mixed with a gadolinium chelate[6,12,17,18] and the T1w 3D GRE sequence is usually performed. Another approach for bright-lumen MRC is based on the acquisition of True-FISP[30,37] and T2w SSFSE[17,30] with a bowel enema consisting of water. Because of the cost of the gadolinium contrast agents used for bowel distension in the bright-lumen approach and the false-positive findings of filling defects caused by air and residual stool,[38,39] 3D GRE-based dark-lumen MRC in conjunction with intravenous gadolinium-chelate has recently been the preferred technique.[6] Dark-lumen MRC requires filling of the colon with water, room air, or carbon dioxide.[6] Besides the 3D GRE sequence, SSFSE and True-FISP sequences are helpful for dark-lumen MRC.[6,17,40] In the present study, the sensitivity of polyp detection by bright-lumen MRC was superior to that of dark-lumen MRC. Overall image quality was also better with the bright-lumen technique, whereas the dark-lumen technique had more susceptibility artifacts from the air and bowel wall interface. In particular, artifacts of True-FISP sequence of dark-lumen MRC from a 3.0 T scanner were so severe that we could detect few small or intermediate size polyps. A previous study also showed that image quality with dark-lumen MRC was not better than that with bright-lumen MRC.[28] To our knowledge, there is no previous study directly comparing the polyp detection sensitivity between bright-lumen and dark-lumen MRC using equivalent sequences.

Image features of True-FISP are characterized by a mixture of T1 and T2 contrast, creating a homogenous bright signal of the colonic lumen filled with water. True-FISP is relatively insensitive to motion, which might be especially helpful in patients who are unable to hold their breath, and has excellent image edge sharpness between lumen and bowel wall, which helps to identify colonic polyps. In the present study, for bright-lumen MRC at 1.5 T the mean detection

sensitivity of True-FISP was 78.6% and 79.2% for all polyps and intermediate size polyps, respectively (Table 2), and the image quality of True-FISP was also either superior or similar to that of the other sequences (Fig. 10). However, True-FISP is relatively sensitive to main magnetic field inhomogeneity, resulting in banding artifacts at the margins of the field of view and at air/tissue interfaces. At 3.0 T, these banding artifacts can be more evident because of increased field inhomogeneity effects. Overall, the imaging quality of True-FISP is better at 1.5 T because the banding artifacts severely compromise the image quality at 3.0 T.[18]

The acquisition of T2w SSFSE with FS is important for polyp detection. This sequence is also valuable to depict edema in or adjacent to the bowel wall, which can be used to differentiate between active and chronic inflammatory changes. In a previous study that performed both bright-lumen and dark-lumen MRC in vivo, the image quality of T2w SSFSE was generally better than that of T1w 3D GRE, mainly due to fewer artifacts and better homogeneity of the bowel content.[28] The overall image quality of the SSFSE sequence is generally expected to be similar at 1.5T and 3T.[18] In the present study, image quality of SSFSE was better at 1.5 T than at 3.0 T and with the bright-lumen technique compared with the dark-lumen technique ($p < 0.05$, respectively). The image quality of SSFSE was also either better or similar to the other sequences for each protocol (Fig. 10), and the mean detection sensitivity of SSFSE in bright-lumen MRC at 1.5 T was 88.4% and 81.3% for all polyps and intermediate size polyps, respectively (Table 2).

T1w 3D GRE sequence has the advantage of high spatial resolution with nearly isotropic voxel size. It also has higher SNR at higher magnetic field strengths, which may improve spatial resolution and allow a considerable reduction in acquisition time. However, it also shows an increase in certain types of artifacts and has the limitation of specific absorption rate (SAR).[18] For example, the blurring artifact at 3.0 T is more influenced by changes in echo time. Therefore,

a maximum sampling bandwidth should be used to obtain the minimum echo time, even though the SNR is decreased.[18] In the present study, 3D GRE at 1.5 T had superior polyp detection and better subjective image quality scores for artifact, colon wall conspicuity, and polyp conspicuity, compared to 3.0 T ($p < 0.05$). We expected higher artifacts at 3.0 T. We also supposed that the worse scores for colon wall conspicuity and polyp conspicuity at 3.0 T might arise from the blurring artifact (Fig. 6b). Recently, T1w 3D GRE has been performed before and after intravenous administration of gadolinium chelate in dark-lumen MRC. However, our colon phantom could not account for the added value of intravenous administration of gadolinium chelate for the dark-lumen MRC. In a previous study, diagnostic confidence was comparable for gadolinium mixture enema-based bright-lumen MRC and air enema-based dark-lumen MRC, although the number of patients included was too small to compare the polyp detection rate between the MRC protocols.[28]

Early reports showed that bright-lumen MRC had comparable accuracy for polyp detection to that of CTC. These studies showed that bright-lumen MRC obtained at 1.5 T had sensitivities and specificities of 93–100% for all polyps and sensitivities of 61-91% for polyps 6–9 mm in diameter.[21,38,41] Other studies using dark-lumen MRC have yielded comparable results. In a previous study, 3D GRE of dark-lumen MRC acquired at 1.5 T had a sensitivity of 93% for polyps 6 mm in diameter or larger.[42] In another study, dark-lumen MRC obtained at 1.5 T had a sensitivity of 100% for adenomas 10 mm in diameter or larger and a sensitivity of 84% for adenomas 6–9 mm in diameter.[31] In contrast, one researcher found that dark-lumen MRC obtained at 1.5 T had a sensitivity of 89% for polyps 10 mm in diameter or larger and a sensitivity of only 38% for polyps 5–9 mm in diameter.[43] In 2005, another study found that 3D GRE-based dark-lumen MRC performed at 1.5 T had a sensitivity of 79% for polyps of all sizes, whereas True-FISP-based bright-lumen MRC had a sensitivity of 68%.[37] In another study, dark-lumen MRC acquired at 1.5 T was found to have a sensitivity of 88% for polyps 6–9 mm in diameter but was not reliable for the

identification of polyps less than 5 mm in diameter.[44] A previous meta-analysis of MRC showed that the per-patient sensitivity for the detection of polyps 10 mm in diameter or larger was 88% and the per-patient specificity was 99%.[45] In a recent study, dark-lumen MRC performed at 3.0 T had a sensitivity of 78.4% for polyps 6 mm in diameter or larger.[22]

In the present study, the sensitivity of 3D GRE in bright-lumen and dark-lumen MRC obtained at 1.5 T was 97% and 58% for polyps 10–16 mm in diameter, 73% and 35% for polyps 6–9 mm in diameter, and 82% and 29% for polyps less than 5 mm in diameter, respectively. The sensitivity of 3D GRE in bright-lumen and dark-lumen MRC acquired at 3.0 T was 75% and 36% respectively for polyps 6 mm in diameter or larger. In addition, when considering the polyp shape, sensitivity of 3D GRE in bright-lumen MRC obtained at 1.5 T was 83% for all polyps, 90% for sessile polyps 4–16 mm in diameter, and 55% for flat polyps 4–10 mm in diameter. These results of bright-lumen MRC were comparable to previous results in the literature using dark-lumen MRC.[22,37,43-45]

There are several limitations of this study. First, the phantom in the present study does not take into account possible artifacts from bowel peristaltic movement or patient respiration motion. However, these effects in vivo can be reduced using breath-hold acquisitions and paralytic agents (scopolamine or glucagon). Use of both supine and prone positions as dual positioning has been recommended in vivo for redistribution of air, feces, and fluid residues that might simulate true polyps. Feces and fluid residues were not present in the phantoms. However, air bubbles could mimic polyps in our phantoms. Therefore we tried to reduce the number of false positives by using both coronal and axial images. Second, simulation of contrast enhancement of bowel wall in our colon phantom was not possible therefore dark-lumen MRC could not account for the added value of intravenous administration of gadolinium chelate, an essential feature of dark-lumen MRC performed in vivo. In clinical practice, polyp detection with dark-lumen MRC depends not only on the identification of

endoluminal soft tissue but also on the enhancement of colonic lesions following intravenous administration of contrast medium. We assume that the use of intravenous administration of gadolinium chelate should improve polyp detection and image quality for 3D GRE-based dark-lumen MRC due to an increase in signal-to-noise ratio. Both polyps and the colonic wall were shown to enhance upon intravenous administration of gadolinium chelate. In a previous study, however, the contrast between enhanced colon wall and the dark lumen was less than expected in all cases.[28] We acknowledge these discrepancies between our ex vivo study and the in vivo situation as a limitation of this study. Nonetheless, our data may help to optimize MRC protocols and provide directions and questions for future research. Finally, the materials used to form polyps were lymph node tissue and raw lean sirloin steak from pigs, which have a slightly different appearance on T1w or T2w imaging than true polyps.[46] However, polyp detection in the present study relies on the identification of endoluminal filling defects or soft tissue using both coronal and axial images. This approach depends on polyp morphology rather than signal intensity on T1w or T2w imaging. Therefore, in our opinion, signal difference between artificial polyps and true polyps did not substantially affect polyp detection in the present study setting.

V. CONCLUSION

Bright-lumen MRC obtained with a 1.5 T scanner provided the greatest polyp detection rate and the best image quality, and SSFSE and 3D GRE sequences were the best sequences for polyp detection. As a noninvasive imaging modality, MRC could be a promising alternative to colonoscopy for the detection of clinically relevant polyps larger than 5 mm in diameter. This study confirmed the high potential of MRC to detect clinically relevant colorectal polyps and masses.

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ABSTRACT (IN KOREAN)

돼지 대장 모형을 이용한 용종 검출을 위한 magnetic resonance colonography 프로토콜 최적화

: 자기장 세기, 대장관 팽창 기법, MRI 촬영 기법이 미치는 영향

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목적: Magnetic resonance colonography (MRC)를 이용하여 대장 용종을 가장 효과적으로 검출하기 위한 프로토콜을 개발하는 것이다. 이를 위해 다음과 같은 세부 목적을 이룬다. 첫째 MRC는 20초 이내의 호흡 정지 시간 동안 고 해상도의 영상을 얻어야 하기 때문에 이에 적합한 MRI sequence를 찾는다. 둘째 대장은 주로 허탈 상태 (bowel collapse)로 있기 때문에 용종을 발견하기 어렵다. 그래서 대장을 팽창시키고, 대장 관내와 대장 벽 사이에 대조도를 높일 수 있는 방법을 찾는다. 셋째 1.5 T 장비와 3.0 T MRI 장비 사이에서 각기 다른 특성이 있기 때문에 MRC 에 적합한 자기장 장비를 알아본다. 여러 가지 촬영기법을 이용하여 대장 용종 검출 민감도를 구하고, 각각의 영상에서 인공물과 장벽 또는 용종의 선명도와 대조도를 바탕으로 영상의 질을 평가하고자 하였다.

재료 및 방법: 60 – 92 cm 의 6개의 돼지 대장을 이용하여 대장 용종 모형을 만든다. 공기, 물, 또는 가돌리늄 조영제를 희석한 물을 이용하여 대장을 팽창시킨다. 최소 6 mm의 용종을 표현할 수 있는 고 해상도를 가지고, 20초 이내에 복부 전체를 촬영할 수 있는 짧은 획득시간을 갖는 영상으로 Two-dimensional (2D) true fast imaging with steady-state precession (True-FISP), T2-weighted fat-suppressed 2D single-shot

fast spin echo (SSFSE), T1-weighted fat-suppressed three-dimensional gradient-echo (3D GRE) 촬영기법을 이용한다. 공기로 대장을 팽창시키고 True-FISP, SSFSE, 3D GRE를 이용하여 dark-lumen MRC를 촬영한다. 그 후 장내 공기를 제거한 후, 물로 다시 팽창을 시켰고 True-FISP과 SSFSE를 이용하여 bright-lumen MRC를 촬영한다. 마지막으로 가돌리늄 조영제를 희석한 물로 팽창시키고 3D GRE를 이용하여 bright-lumen MRC를 촬영한다. 모든 촬영은 1.5 T와 3.0 T MRI 장비에서 촬영한다. 두 명의 영상의학과 전문의가 무작위 순서로 영상을 보면서 용종 유무를 4-point scale을 이용하여 판단한다. 인공물, 대장 벽의 선명도, 용종의 선명도, 용종의 대조도를 5-point scale을 이용하여 판단한다.

결과: 용종 검출을 하는데 1.5 T 장비가 3.0 T 장비보다 용종 검출 민감도가 월등히 높았고, 인공물이 적어 영상의 질이 더 우수했다. 또한 bright-lumen 기법이 dark-lumen 기법보다 민감도가 월등히 높았고 영상의 질 또한 뛰어났다. 결과적으로는 1.5 T 장비에서 촬영한 bright-lumen MRC 용종 검출 발견율과 영상의 질이 가장 우수했다. Sequence 별로 보자면, 물 또는 가돌리늄 조영제를 희석한 용액으로 대장을 팽창시킨 bright-lumen MRC에서 이용한 SSFSE와 3D GRE가 용종 발견율 및 영상의 질이 가장 뛰어났다.

결론: 대장암 선별검사에서 MRC가 유용하게 쓰일 수 있다는 것을 보여주었다. 1.5T 장비에서 촬영한 bright-lumen 기법이 가장 효과적이었고, SSFSE와 3D GRE 촬영기법이 가장 우수하였다. 추후 MRC 에서 더 좋은 프로토콜 개발 할 때 본 연구 결과가 기초가 될 수 있을 것이다.

핵심되는 말: 대장, 용종, 자기공명영상, 민감도, 모형