State of the Art MR Enterography Technique

Manjil Chatterji, MD,* Jeff L. Fidler, MD,† Stuart A. Taylor, MD,‡ Sudha A. Anupindi, MD,§
Benjamin M. Yeh, MD,¶ and Flavius F. Guglielmo, MD‖

Abstract: Magnetic resonance enterography (MRE) is a well-established imaging technique that is commonly used for evaluating a variety of bowel diseases, most commonly inflammatory bowel disease which is increasing in prevalence. Inflammatory bowel disease is composed of 2 related, but distinct disease entities: Crohn disease (CD) and ulcerative colitis. In ulcerative colitis, inflammation is generally limited to the mucosa and invariably involves the rectum, and often the more proximal colon. CD is typified by transmural inflammation with skip lesions occurring anywhere from the mouth to anus, but characteristically involves the terminal ileum. The transmural involvement of CD may lead to debilitating ulceration and, ultimately, development of sinus tracts, which can be associated with abscesses and fistulae as extraenteric manifestations of the disease. Because much of the small bowel and extraenteric disease cannot be adequately assessed with conventional endoscopy, imaging plays a crucial role in initial diagnosis and follow-up. MRE does not use ionizing radiation which is important for these patients, many of which present earlier in life and may require multiple imaging examinations. In this article, we review the clinical indications, patient preparation, and optimal technique for MRE. We also discuss the role and proper selection of intravenous gadolinium-based contrast material, oral contrast material, and antiperistaltic agents, including pediatric considerations. Finally, we review the recommended and optional pulse sequence selection, including discussion of a "time-efficient" protocol, reviewing their utility, advantages, and limitations. Our hope is to aid the radiologist seeking to develop a robust MRE imaging program for the evaluation of bowel disease.

Key Words: antiperistaltic agents, Crohn disease, enteric contrast agents, MR enterography pulse sequences, MR enterography technique, oral contrast agents

(*Top Magn Reson Imaging* 2021;30:3–11)

Inflammatory bowel disease (IBD) is composed of 2 major disease entities: Crohn disease (CD) and ulcerative colitis. Although the pathogenesis of IBD remains unknown, there is considerable overlap in genetic, immune, dietary, and lifestyle risk factors which may be associated with both diseases. In ulcerative colitis, inflammation is characteristically limited to the mucosa and invariably involves the rectum, although other segments of the colon can also be involved, typically in a continuous fashion. CD is typified by transmural inflammation with skip lesions occurring anywhere from the mouth to anus, but characteristically involving the terminal ileum. The transmural involvement of CD may lead to debilitating ulceration and, ultimately, development of sinus tracts, which can be associated with abscesses and fistulae as extraenteric manifestations of the disease extend into the mesentery and peritoneal cavity. The incidence and prevalence of IBD has been generally increasing in the United States, with some studies suggesting an increase of >40% between 2000 and 2011.[1,2] Because much of the small bowel and extraenteric disease cannot be adequately assessed with conventional endoscopy, imaging plays a crucial role in the diagnosis and follow-up of patients with IBD. In this article, we review the optimal magnetic resonance enterography (MRE) technique and discuss the appropriate clinical indications and patient preparation, the use of intravenous (IV) gadolinium-based contrast material, oral contrast material, and antiperistaltic agents, and pulse sequence selection, including pediatric considerations.

MR ENTEROGRAPHY INDICATIONS

MRE is a well-established imaging technique that is commonly used for evaluating bowel diseases. Although MRE is useful to assess a number of bowel conditions, the most common reason to perform MRE is to diagnose, monitor, and detect complications of IBD (Table 1).[3–10] MRE has several significant advantages over computed tomography (CT) enterography (CTE) and traditional barium-based fluoroscopic examinations (ie, small bowel series and enteroclysis). MRE does not use ionizing radiation which is important for patients with IBD, many of which present earlier in life and may require multiple imaging examinations during their lifetime to monitor treatment.[3,4,6–12] MRE's higher contrast resolution and multiphasic post-contrast sequences compared to CTE makes MRE more sensitive for the detection of bowel wall hyperemia and potentially fibrosis, and it provides greater ability to provide insights into the severity of small bowel inflammation.[4] MRE also offers small bowel motility evaluation with "cine" sequences, a feature not available with CTE, which can help identify small bowel inflammation, strictures, adhesions, and masses.[4,9,12,13] Finally, compared to CTE, MRE's higher soft tissue contrast resolution provides better evaluation of the perianal region to identify perianal fistulas, which can occur in up to 25% of patients with CD, along with possible associated abscesses.[4]

PATIENT PREPARATION

Thoughtful preparation of the patient for MRE can help the patient feel comfortable undergoing the examination and improve the quality of the acquired images. Patient education should include emphasis on the need for fasting and compliance with oral contrast material drinking, information on the duration of the scan, and importance of lying still and following breathing instructions. It is critical to discuss with the patient the possibility of transient loose stool resulting from the oral contrast agent and the need for the patient to ensure access to a restroom for an hour or more after the scan.[14]

Many practices advocate for a 4- to 6-hour fast, with the exception of clear liquids and regular medications, before the MRE examination. Fasting minimizes the presence of potentially

From the *Department of Radiology, Weill Cornell College of Medicine, New York, NY; †Department of Radiology, Mayo Clinic, Rochester, MN; ‡Centre for Medical Imaging, University College London, London, UK; §Department of Radiology, The Children's Hospital of Philadelphia, Philadelphia, PA; ¶Department of Radiology and Biomedical Imaging, University of California, San Francisco, CA; and ‖Department of Radiology, Thomas Jefferson University Hospital, Philadelphia, PA.
Address correspondence to Manjil Chatterji, MD, Department of Radiology, Weill Cornell College of Medicine, 1305 York Ave, 305, New York, NY 10065 (e-mail: mac7011@med.cornell.edu).

TABLE 1. Indications for Magnetic Resonance Enterography

Diagnosis of IBD—evaluate disease activity, extent, and distribution
Follow up known IBD—evaluate disease activity and treatment response
Evaluating possible IBD—related complications such as stricture, obstruction, or penetrating disease (eg, fistula, sinus tract, abscess, or inflammatory mass)
Small bowel masses and polyps
Non-IBD enteritis (eg, infection, vasculitis, or treatment-related enteritis)
Adhesive disease and intermittent or low-grade small bowel obstruction
Celiac disease

Table modified, with permission, from reference.[6]

confusing enteric contents which can mimic polyps and masses. Fasting may also improve compliance with drinking the large volume of oral contrast material required for optimal bowel evaluation.

A second concern for MRE is T1-weighted hyperintense material that is commonly present in the colon and at times the distal small bowel, even after an overnight fast. Such bright T1-weighted signal may interfere with the visualization of distal bowel wall hyper- and hypoenhancement after IV gadolinium-based contrast material administration. Although bowel cleansing to remove high T1-weighted signal bowel contents is not currently in wide practice for MRE,[15] cathartics may of value for patients with suspected colonic and rectal disease. In patients with uncleansed bowel, diffusion-weighted imaging (DWI) should be included to improve diagnostic accuracy.[16]

A third consideration is gas in the bowel, which is of particular concern in the pediatric population. Large amounts of bowel gas may cause artifacts in the bowel and adjacent structures. Although little has been published on gas reduction for MRE, approaches to this issue include avoiding foods that cause bloating for at least a day before the examination, encouraging clear liquids up until the time of the examination, keeping children calm to avoid excessive crying which may result in increased swallowed air, and minimizing face-mask bag ventilation which may force air into the bowel if imaging is performed under sedation/general anesthesia (GA). In addition, upper endoscopy and colonoscopy right before an MRE should be avoided if at all possible to minimize gas introduced by the procedures.

Patients who have claustrophobia may benefit from an anxiolytic which may be taken orally. Patients may take their own anxiolytic, or, if needed, one may prescribe a short-acting low-dose benzodiazepine, as allowed by local policies and guidelines.

Infants and young children with very early onset IBD, defined as patients younger than 5 years of age, who need MRE for their IBD will usually require GA. Other subgroups of children who may require GA for their examination are those who are developmentally delayed and/or have autism. These studies need to be closely coordinated with anesthesia and can be performed safely. However, there are a few important elements in patient preparation: (1) patients are intubated and need to be imaged in the supine position, (2) oral contrast material volume is reduced to 5 to 10 mL/kg (compared to nonsedated pediatric cases, in which case the dose is 20 mL/kg), and (3) glucagon is not administered due to the concern for ileus exacerbation.[17] MRE with GA studies are usually shorter examinations and can be performed safely with occasional minor side effects/adverse events associated with GA.[17] Alternatively, the use of mock MRI scanners, 3D virtual MRI compatible goggles, child life specialist consultation, video goggles to view movies, other audiovisual devices, and pet therapy have been successful strategies to reduce anxiety and the need for sedation/GA and improve compliance in children.[18]

ENTERIC CONTRAST AGENTS

The primary goal of enteric contrast material in bowel imaging is to distend the bowel and reduce susceptibility artifacts by displacing air. Collapsed bowel can mimic bowel wall thickening and lead to the overdiagnosis of bowel pathology, or conversely may hide polyps and other entities, highlighting the indispensable role of oral contrast material in MRE.[19] Oral contrast material improves the diagnostic performance of the examination, notably in the diagnosis of active disease involving the terminal ileum.[20] Although many oral contrast agents have been described in the literature,[21–23] biphasic agents that are both T2-weighted hyperintense (bright) and T1-weighted hypointense (dark) are generally preferred agents for MRE to accentuate mucosal enhancement and assessment of bowel wall thickening. Commonly used biphasic agents include 0.1% low-density barium suspension (NeuLumEX, formerly VoLumen, Bracco Diagnostics, Princeton, NJ), mannitol, sorbitol, polyethelyene glycol (PEG) and methylcellulose. Water itself is well tolerated and also demonstrates biphasic properties, but rapid absorption limits its intended effect in the distal small bowel, where it often matters most.[14] Young et al[24] found superior distension of the bowel with low-density barium suspension and PEG compared with water or methylcellulose, although PEG was the least tolerated of all agents due to diarrhea. Multiple recent studies have demonstrated similar distension efficacy of a flavored beverage containing sugar alcohols (Breeza; Beekley Corp., Bristol, CT) when compared with a low-density barium suspension, although with preferred palatability and texture profile.[14,25] These findings are reflected in a survey of academic radiology groups represented by members of the Society of Abdominal Radiology Crohn's Disease Disease-Focused Panel (DFP), with >80% of institutions using either a flavored beverage with sugar alcohol or low-density barium suspension.[15] Iron-based monophasic oral contrast darkens the bowel lumen signal on both T1- and T2-weighted images and can improve visualization of bowel wall edema and tumors on T2-weighted images and assessment of bowel wall enhancement after IV contrast material administration. Low patient tolerance, however, has limited the use of iron-based agents to date.

Whatever the agent, ingestion of a large volume of contrast is necessary to best distend the bowel. For typical assessment of the bowel, enteroclysis is unnecessary as patient-directed oral intake is much better tolerated with similar diagnostic efficacy and reproducibility.[26,27] Suggested ingestion volumes range from 1000 to 1500 mL, but can anecdotally vary widely based on patient willingness, tolerance, size, and history of bowel resection, including the presence of an ileostomy. Most commonly oral contrast volumes in children are weight-based at ~20 ml/kg, up to an adult maximum dose. Timing of ingestion relative to the time of scanning is paramount but can be difficult to predict – scanning too soon after ingestion leads to inadequate distension of the distal small bowel while scanning too late (>60 minutes after ingestion) can result in a majority of the contrast material passing completely through the small bowel, distending only the colon. At most institutions surveyed by the DFP, patients are instructed to drink the total volume in 3 divided aliquots over 30 to 60 minutes, as tolerated. An additional 250 to 500 mL of water or contrast can be administered on the table just before imaging to distend the stomach and proximal small bowel.

To improve compliance with the ingestion of oral contrast material in children a few strategies have been helpful including (1) mixing oral contrast agents with sugar-free flavorings to be palatable, (2) assigning nursing or child life staff that can encourage

TABLE 2. Gadolinium-based Contrast Agents

Generic Name	Trade Name	ACR Class	Structure	T1 Relaxivity at 1.5 T (L/mmol · s)	Hepatobiliary Excretion (%)
Gadoterate meglumine	Dotarem	II	Macrocyclic	+ (3.6)	0
Gadoteridol	ProHance	II	Macrocyclic	++ (4.1)	0
Gadopentetate dimeglumine*	Magnevist	I	Linear	++ (4.1)	0
Gadoversetamide*	Optimark	I	Linear	++ (4.3)	0
Gadodiamide*	Omniscan	I	Linear	++ (4.3)	0
Gadobutrol	Gadavist/Gadovist	II	Macrocyclic	+++ (5.2)	0
Gadobenate dimeglumine	MutiHance	II	Linear	++++ (6.3)	3−5

*Off-market in the United States.
ACR indicates American College of Radiology.

drinking, and (3) placing the patient in the right lateral position to help fill the proximal small bowel and reduce gastric over-distention.

INTRAVENOUS CONTRAST AGENTS

With CD, active inflammation increases blood flow to the bowel reflected in mural hyperenhancement after the administration of IV contrast material. In numerous studies, bowel wall enhancement has been shown to correlate with disease activity and active inflammation.[28−31] For this reason, IV contrast material is currently recommended unless (a) IV access cannot be established; (b) there is concern for a severe gadolinium-based contrast material allergy for which pre-medication is not possible or advisable; (c) gadolinium exposure is contraindicated (eg, pregnancy); or (d) the risks of gadolinium-associated nephrogenic systemic fibrosis outweigh the benefit in patients with chronic renal failure. Of the commercially available extracellular gadolinium-based contrast agents that can be used for MRE (Table 2), gadobenate (MultiHance; Bracco Diagnostics, Monroe Township, NJ) is often cited as the agent of choice given its superior T1 relaxivity profile. If a patient is to undergo multiple examinations requiring gadolinium-based contrast material; however, a more stable macrocyclic agent such as gadobutrol, gadoterate meglumine, or gadoteridol could be considered though the American College of Radiology classifies all 4 agents as risk Group II agents, which are associated with "few, if any" unconfounded cases of nephrogenic systemic fibrosis.[32,33] The standard dose for all agents used for MRE is 0.1 mmol/kg administered at 2 mL/s, after which multiphase dynamic 3D fat-suppressed T1-weighted gradient recalled echo images are acquired to evaluate temporal enhancement of the bowel wall, which peaks 45 to 50 seconds after injection (the "enteric" phase). Images are typically acquired in the coronal plane, though some institutions also perform a delayed axial (up to 8 min post-injection), which some authors have suggested improves lesion detection and disease grading (including fibrosis detection).[34] The DFP survey revealed all but one institution

regularly administered IV contrast material for MRE, routinely acquiring 2 to 5 (median 4) post-contrast phases including subtraction images.[15] If gadolinium-based contrast material is contraindicated, there are data suggesting noninferiority of a noncontrast protocol relying on T2-weighted sequences in conjunction with DWI in well-prepared patients that do not have penetrating complications of CD.[35]

ANTIPERISTALTIC AGENTS

A key requisite for high-quality MRE is the absence of bowel wall motion on acquired images. Peristalsis is increased due to the stimulatory effect of ingested oral contrast material on the bowel, which may cause motion artifact, impeding interpretation. Although diagnostic accuracy remains high without the use of antiperistaltic agents,[36] international guidelines generally recommend routine administration of the antiperistaltic agent glucagon in the United States or hyoscine butylbromide outside the United States.[4,37] The DFP survey reported 13/16 (81%) of institutions routinely administered antiperistaltic agents, although there was variability in agent, dose, and timing of administration.[15] Although this partly reflects differences in regulatory permissions between different countries, there are distinct pharmacokinetic differences between agents which may influence choice.

On average, subjective enteric MRE image quality is improved by administration of either glucagon[38] or hyoscine butylbromide,[39] but volunteer studies reveal variability in time of onset, efficacy, and duration of effect (Table 3). Gutzeit et al[40] compared the effect of IV and intramuscular (IM) glucagon and hyoscine butylbromide on bowel peristalsis in 6 volunteers using cine MRI sequences. They reported a slightly shorter time of onset for aperistalsis following 1 mg IV glucagon than 40 mg IV hyoscine butylbromide (mean 65 vs 85 s). IM administration delayed onset considerably for both agents, and was associated with increased variability of effect. Mean duration of action was slightly longer for IV glucagon than for IV hyoscine butylbromide. Froehlich et al[41] reported similar findings after comparing 40 mg IV

TABLE 3. Comparison of Antiperistaltic Agents Based on Cine Motility Magnetic Resonance Imaging[40,41,46]

Agent	Route of Administration	Typical Dose	Typical Time to Onset	Typical Duration of Effect*	Quality of Aperistalsis*	Common Side Effects	Cost
Glucagon	IM or IV†	0.5−1 mg	1/2−1 min (IV) 12 min (IM)	18−23 min (IV); 28 min (IM)	+++	Nausea, emesis	+++
Hyoscine butylbromide	IM or IV†	20−40 mg	1/2−1.5 minutes (IV) 5 min (IM)	7−21 min (IV); 17 min (IM)	++	Dry mouth, tachycardia, blurred vision	+
Hyoscyamine sulfate	Sublingual/oral	0.125−0.5 mg	2−3 min	4−6 h	+	Dry mouth, blurred vision	++

*Based on direct data from MRI cine motility sequences.
†Intravenous administration produces a more reliable antiperistaltic effect that intramuscular.

hyoscine butylbromide with 1 mg IV glucagon in 10 volunteers, although actual timings differed from those of Gutzeit et al,[40] likely reflecting differences in methodology for evaluating bowel loop peristalsis. Glucagon produced complete aperistalsis in all 10 volunteers versus 5 of 10 for hyoscine butylbromide.

Administered doses are typically 0.5 to 1 mg for glucagon and 20 to 40 mg for hyoscine butylbromide, with a minority of centers using a patient weight-adjusted dose.[15,37] The optimal timing of administration and the potential benefit of splitting the dose remains unclear, with variation in clinical practice.[15] The sensitivity of MRE sequences to peristaltic artifact influences the timing of administration. Pre- and post-contrast T1-weighted 3D gradient recalled echo sequences are particularly susceptible, balanced steady state free procession sequences are relatively immune, whereas T2-weighted single-shot fast spin-echo (SSFSE) sequences are somewhere in between. Finally, the sensitivity of DWI for identifying active CD may be improved after administering antiperistaltic agents.[42]

Administration of antiperistaltic agents before post-contrast sequences either as a single dose or part of a split dose approach is common practice and is effective in improving T1-weighted image quality.[38] Based on duration of action (Table 3), it may be expected that an upfront single dose may "wear off" before the end of the MRE protocol, typically when DWI and delayed T1-weighted post-contrast images are acquired. Recent work has confirmed the superiority of a split-dose hyoscine butylbromide over a single-dose technique.[43] Antiperistaltic agents should be administered after cine motility sequences have been acquired since these agents decrease bowel motility.

A further consideration is the side effect profile of antiperistaltic agents. Glucagon may cause nausea in about 50% of patients,[38] sometimes several hours after administration. This side effect can be reduced by injecting at a slower rate.[44] Hyoscine butylbromide may temporarily cause dry mouth, tachycardia, and blurred vision, and, although it has an excellent safely profile, is contraindicated in unstable cardiac conditions.[45] Alternative antiperistaltic medications such as sublingual hyoscyamine sulfate are reported to be clinically ineffective (Table 3).[46]

MRE is certainly feasible without antiperistaltic agents, but consensus guidelines generally recommend its use. Both glucagon and hyoscine butylbromide are effective and most reliable when administered intravenously. Glucagon tends to have a slighter shorter time of onset and longer duration of effect.

In pediatric patients it is not uncommon to give the glucagon as a split dose of 0.25 mg IV (total of 0.5 mg IV) 1 dose either at the beginning of the study or after cine imaging (if performed) and the second before IV contrast material administration. In addition to injecting glucagon slowly, an adequate saline flush is beneficial to help reduce the side effect of emesis. In a 2013 pediatric study of the effects of glucagon on MRE quality, children (n = 50) received between 40 and 70 mL of saline flush following the glucagon administration and of these patients only 8% experienced emesis.[38]

MRE PULSE SEQUENCES

There currently is no consensus on the appropriate pulse sequences for MRE. However, there is general agreement on the main sequences which should be performed and other sequences which may be considered optional. There have been 2 publications by a panel of experts with recommendations on MRE technique.[4,37] These recommended and optional sequences will be reviewed in the subsequent paragraphs with a brief discussion on their utility, advantages, and limitations (Table 4).

PATIENT POSITIONING

Patients can be scanned either supine or prone. The prone position has some theoretical advantages. Because of compression of bowel loops, the number of required images in the coronal plane can be reduced. Prone positioning may also reduce motion artifact from the anterior abdominal wall. Prone positioning allows the patient to look outside the bore of the magnet and may reduce claustrophobia. However, some patients may be more comfortable in the supine position including patients with ostomies. Children who undergo GA for the MRE and those children where audiovisual devices are needed to reduce anxiety will need to be scanned in the supine position.

Recommended Sequences

T2-weighted and Balanced Steady-state Free Precession Sequences (Fluid-sensitive Sequences)

There are 2 main types of fluid-sensitive sequences recommended for MRE (Fig. 1), T2-weighted SSFSE and balanced steady-state free

TABLE 4. Recommended and Optional Magnetic Resonance Enterography Pulse Sequences

Sequence	Plane	Maximum Slice Thickness/Gap	Comment
Recommended sequences			
SSFSE	Coronal	5/0	
SSFSE with fat-suppression	Coronal	5/0	
SSFSE	Axial	6/0	Alternatively, can perform BSSFP
3D T1W GRE with fat-suppression	Coronal	4/0	Unenhanced followed by 3 dynamic postcontrast phases beginning with a 45 s scan delay. Supplemental 2D FSPGR can be performed if 3D image quality is suboptimal
3D T1W GRE with fat suppression	Axial	6/0	Supplemental 2D FSPGR can be performed, if 3D image quality is suboptimal
Optional sequences			
DWI	Coronal or axial	5–6/0	Coronal faster but prone to more artifacts. Axial longer but improved image quality. b-values of up to 800–1000 sec/mm^2. Consider SMS technology if available
Cine BSSFP or SSFSE	Coronal	7–10/0	25–30 phases per slice location
3D T1W GRE with fat-suppression	Coronal	4/0	5–7 min delays to detect fibrosis

3D indicates 3-dimensional; FSPGR, fast spoiled gradient echo; GRE, gradient recalled echo; SMS, simultaneous multislice; T1W, T1 weighted.
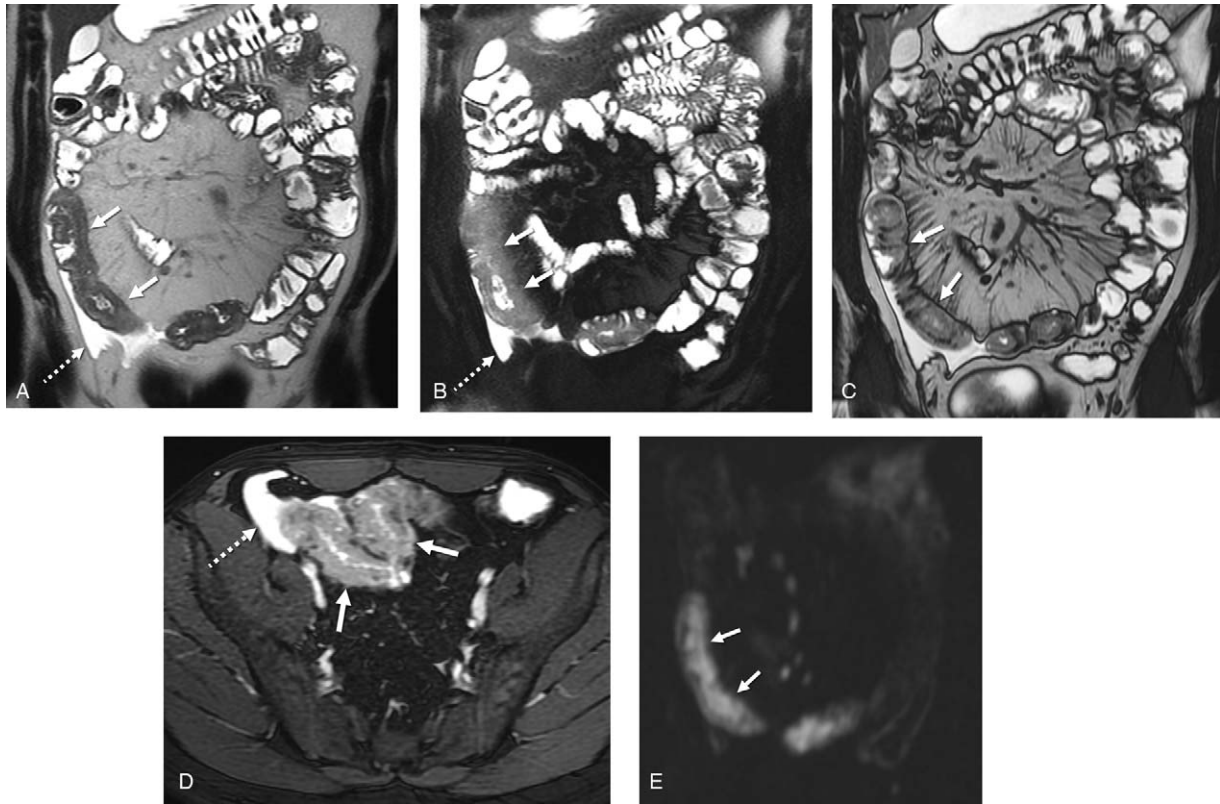
FIGURE 1. Examples and comparison of T2-weighted and DWI MRE sequences. Coronal single-shot fast spin-echo (SSFSE) (A), coronal SSFSE with fat-suppression (B), coronal balanced steady state free precession (BSSFP) (C), axial BSSFP with fat-suppression (D), and coronal DWI with a *b* value of 1000 s/mm^2 (E) show characteristic findings of active inflammation of Crohn disease in the terminal ileum (arrows) with wall thickening, intramural edema (B and D) and restricted diffusion (E). Note the perienteric fluid (dashed arrow). Note the better visualization of the mesenteric structures on the BSSFP sequence (C) compared to the SSFSE (A). Given that the BSSFP sequence also has T1-weighting, the bowel wall has higher signal (D) than on the SSFSE sequence (B) when fat-suppression is applied. Therefore, most studies have assessed and quantitated intramural edema on the more true T2-weighted SSFSE sequence. In this case, note that there is no significant image distortion on the DWI images acquired in the coronal plane (E).

precession (BSSFP). These fast sequences can be performed during breath-holding and, because each image acquisition is very rapid, are not as susceptible to motion artifact as the other MRE sequences. Coronal and axial acquisitions can be performed to visualize the bowel in 2 planes, as certain abnormalities may be more perceptible in 1 plane. T2-weighted sequences are useful for evaluating bowel wall signal and thickness and can demonstrate the subtle inner luminal irregularities associated with ulcerations commonly seen in CD. They also provide an excellent overview of the entire abdomen.[4,10] BSSFP sequences are T2-like sequences which have combined T2 and to a lesser extent T1 weighting. These sequences provide a more homogenous appearance to the intraluminal fluid than the SSFSE which frequently demonstrate multiple areas of flow void artifact secondary to the movement of fluid in the bowel lumen and that can mimic filling defects. Therefore, the BSSFP sequence may be more useful detecting intraluminal masses. BSSFP also provides improved visualization of mesenteric structures such as lymph nodes and blood vessels. BSSFP sequences can be added to supplement the T2W SSFSE sequences or as a replacement for one of the planes.
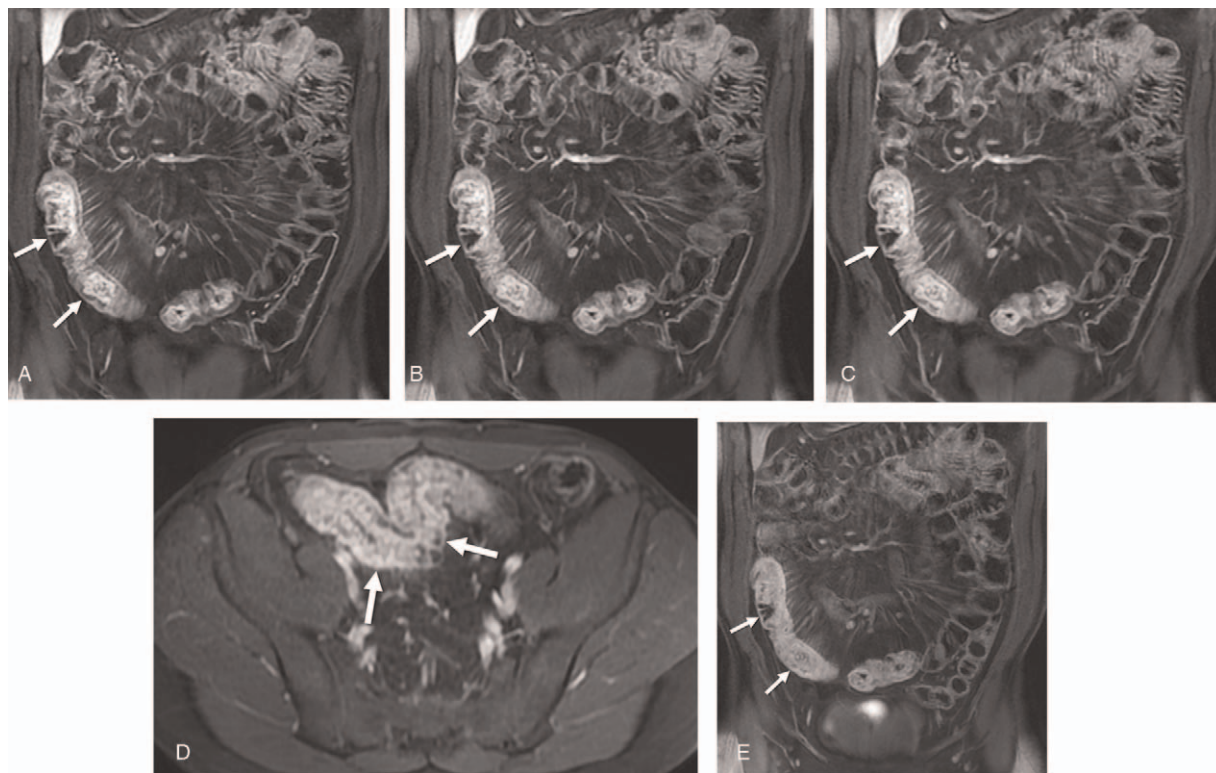
Fat-suppressed T2-weighted Sequences

T2-weighted sequences with fat suppression (Fig. 1) are used to help demonstrate intramural edema, a sign of active inflammation.[4] Because the SSFSE sequence is more T2 weighted than BSSFP, most

sites include a fat-suppressed SSFSE sequence in the protocol. Longer conventional T2-weighted sequences are usually not needed. Since the main purpose of these sequences is to evaluate for edema and inflammation in the bowel wall and surrounding mesenteric fat, one acquisition plane is usually sufficient. Also, since the number of slices required during a coronal acquisition is significantly fewer than in the axial plane, coronal sequences can be performed faster with less breath holds.

Contrast-enhanced sequences

IV contrast enhancement is helpful to demonstrate bowel wall active inflammation and penetrating disease, in identifying abscesses and differentiating abscess from inflammatory mass, and in evaluation of the vasculature.[4] Although most experts currently recommend the administration of IV contrast material, there is no consensus on how this should be performed. In general, most institutions perform dynamic contrast-enhanced fat-suppressed 3D T1-weighted gradient recalled echo sequences in the coronal plane during breath holding and include 3 or more phases (Fig. 2). Multiple phases are helpful as the rate of bowel wall enhancement may vary (with earlier enhancement suggesting more active inflammation) and some of the acquisitions may have motion artifacts. Following the dynamic coronal acquisition, an axial acquisition (Fig. 2) should also be performed to evaluate the bowel in an additional plane and provide visualization of

FIGURE 2. Examples of contrast-enhanced sequences. Three dynamic contrast-enhanced fat-suppressed T1-weighted 3D gradient recalled echo phases beginning at a 45-second scan delay (A–C), followed by an axial T1-weighted 3D gradient recalled echo sequence (D), and 7-minute delayed coronal postcontrast sequence on the same patient in Figure 1. Images demonstrate findings consistent with active inflammation (arrows), including wall thickening, stratified mural hyperenhancement, and engorged vasa recta. Also note the asymmetry with sacculations along the antimesenteric border.

the anterior and posterior abdominal wall which can be excluded on the coronal dynamic coverage. Because the 3D T1-weighted sequences are susceptible to both respiratory motion and bowel peristalsis, breath-holding and spasmolytic agents should be utilized to reduce motion artifacts.

If high-quality 3D T1-weighted gradient recalled echo images cannot be obtained, 2D gradient recalled echo (with or without spoiling) sequences can be performed. 2D T1-weighted sequences are long and may require multiple breath holds which may lead to respiratory misregistration. Therefore, parameters should be adjusted to limit the number of breath holds.

Optional Sequences

Diffusion-weighted Imaging

Restricted diffusion, as shown by high signal intensity on higher *b* value DWI images in the range of 800 to 1000 s/mm^2, has been shown to be associated with severe active inflammation[10,47–49] (Fig. 1). However false positives are common and may be related to collapsed bowel or other difficult to define etiologies.[48] Therefore, if performed, the DWI findings should be correlated with the conventional recommended sequences. DWI sequences are significantly longer than the other MRE sequences and therefore some sites acquire them in the coronal plane to reduce scan time. For example, a coronal acquisition can be performed in 2 to 3 minutes, whereas an axial acquisition takes approximately 5 minutes (Fig. 3A–B). However, coronal acquisitions are plagued by image distortion which can be excessive on some scanners. If the distortion is too significant to

allow interpretation, DWI should be performed in the axial plane. New technology such as simultaneous multi-slice or multiband (Fig. 3) excitation is becoming more widely available for abdominal use and allows acquisition of multiple slices at the same time, including DWI. Images are most commonly assessed in a qualitative manner.

Cine Imaging

Multiphase BSSFP or SSFSE can be performed to visualize bowel peristalsis. Decreased peristalsis can be seen in areas of active inflammation or fibrosis and the presence of decreased peristalsis may increase a reader's level of confidence when visualizing subtle abnormalities on conventional images.[13] Cine images should be performed before spasmolytics are administered as their use decreases bowel peristalsis. However, despite the administration of spasmolytics, some peristalsis is usually still visible. Cine images are usually performed in the coronal plane. These can be performed during breath-holding or free breathing. Breath holding provides improved image quality, however, requires longer scan times. Slice thickness can be acquired at 7 to 10 mm. Thinner slices require more acquisitions to cover the small bowel, however, may better demonstrate more subtle findings. To reduce scan time, the coverage should be limited to the small bowel.

Delayed Postcontrast Imaging

Delayed T1-weighted gradient recalled echo sequences can be performed up to 8 minutes postcontrast material injection (Fig. 2) and may be helpful in identifying delayed bowel wall enhancement due
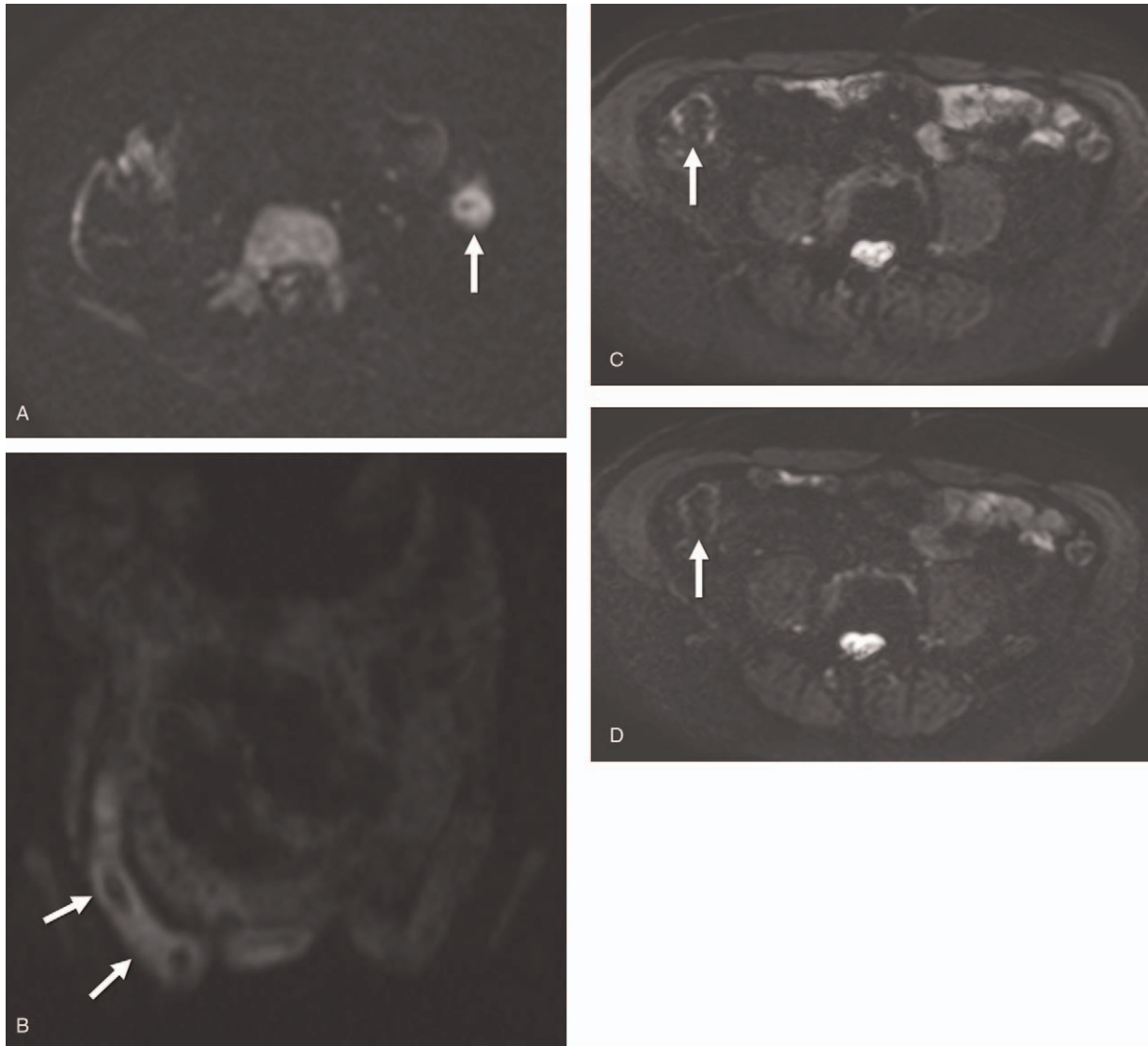
FIGURE 3. Examples of DWI Sequences. Axial DWI image with a b value of 1000 s/mm^2 (A) shows active inflammation in the descending colon (arrow). Coronal DWI with a b value of 1000 s/mm^2 (B) in different patient shows active inflammation in the terminal ileum (arrow). The total time for the coronal acquisition in B was 2 minutes compared to 8 minutes for the axial acquisition in A. Multi-band DWI in a third patient with factors of 2 (C) and 3 (D) shows subtle terminal ileal inflammation (arrows). A multiband factor of 2 allows simultaneous acquisition of 2 slices reducing overall scan time.

to fibrosis,[50] while potentially improving lesion detection and disease activity grading. These sequences should be acquired using similar parameters as the dynamic and early postcontrast sequences so that adequate comparison can be performed.

Protocol Standardization

The MRE protocol is flexible and can be adjusted to individual institutional preferences or to overcome technology limitations that may be present. Despite the generalized agreement of the recommended sequences, a recent publication by the Society of Abdominal Radiology Crohn's Disease DFP showed variability in the sequences and acquisition planes performed by their member's institutions.[15] Because of the current variability in protocols among the DFP members, the DFP is in the process of developing a more standardized protocol.

Protocol Organization Considerations

The total acquisition time of the MRE protocol should ideally be <30 minutes.[37] Historically, MRE has been performed with the T2-weighted sequences acquired at the beginning of the examination followed by the administration of IV spasmolytic agents just before the contrast-enhanced sequences. However, reorganization of this approach can provide improved efficiency, decreased scan times, and perhaps improved image quality. An example of this alternative approach is the "Time-Efficient MRE Protocol" that is currently used at the Mayo Clinic and is described in the following paragraphs.

Spasmolytics are helpful to reduce bowel peristalsis and decrease motion artifact on the contrast-enhanced T1-weighted gradient recalled echo sequences. IV or IM administration of an antiperistaltic provides rapid and reproducible effects and usually is

TABLE 5. Sample ''Time-Efficient'' Magnetic Resonance Enterography Protocol

Sequence	Plane	Maximum Slice Thickness/Gap	Matrix	Comment
				Administration of antiperistaltic medication
BSSFP with fat-suppression	Axial	6/0	192 × 340	
DWI	Coronal	5/0	80 × 128	*b* values of 0, 100 and 1000
3D T1W GRE with fat-suppression	Coronal	4/0	320 × 320	Unenhanced imaging followed by 3 dynamic postcontrast phases beginning with ∼45 s scan delay
3D T1W GRE with fat-suppression	Axial	5–6/0	256 × 192	
SSFSE	Coronal	5/0	384 × 224	
SSFSE with fat-suppression	Coronal	5/0	384 × 224	
BSSFP	Coronal	5/0	192 × 340	
3D T1W GRE with fat suppression	Coronal/axial	4/0	320 × 320	7 min delay

3D indicates 3-dimensional; GRE, gradient recalled echo; T1W, T1 weighted.

injected immediately before the contrast-enhanced images. This requires pausing the examination, removing the patient from the bore of the magnet, slowly injecting the antiperistaltic, and waiting 1 to 2 minutes to ensure that the patient does not develop nausea or vomiting before restarting the examination. At many institutions, nurses (and rarely physicians) are required to inject the agent which can lead to additional delays. If regulations allow a technologist to inject the agent, this can help eliminate delays related to nursing. An alternative approach is to administer the antiperistaltic at the beginning of the examination when the patient is placed on the scanner table. This prevents the need to halt the examination in the middle, but may diminish the quality of cine sequences if these are performed.

If an antiperistaltic is administered at the beginning of the examination, contrast-enhanced sequences should be performed earlier in the examination, closer to the administration time, to achieve the maximum aperistaltic effect. Most fluid-sensitive sequences can be performed after IV contrast material without negative impact although some should be performed before contrast to prevent any confounding appearances. For example, fat-suppressed BSSFP sequences which include both T2- and T1-weighting will show bowel wall enhancement simulating intramural edema. DWI sequences can be performed either before or after IV contrast material, although image quality may be better before administering contrast.

Another potential advantage of moving motion-sensitive contrast-enhanced T1-weighted gradient recalled echo sequences to earlier in the examination is improved image quality. All MRE sequences are performed during breath holding. If the contrast-enhanced sequences are performed at the end of the examination, the patient may fatigue and not able to hold their breath adequately leading to significant motion artifact, image blurring, and suboptimal image quality. This approach has been performed at the Mayo Clinic for the last 2 to 3 years with a significant decrease in scan times. This sample ''Time-Efficient MRE Protocol'' is shown in Table 5.

There is a potential limitation of the above approach if using cine images for diagnostic purposes. The decreased peristalsis induced by the administration of an antiperistaltic agent could potentially mimic areas of altered motility which can be seen with inflammation and fibrosis. Therefore, if cine images are performed these should ideally be performed before administration of antiperistaltic medication, even though some peristalsis can still be visible after administration.

CONCLUSIONS

MRE is a robust imaging tool for evaluating patients with IBD without the potentially harmful effects of the ionizing radiation associated with CT enterography. Understanding the appropriate clinical indications for imaging and proper imaging technique is essential to obtain high-quality images of the bowel for accurate evaluation and diagnosis of CD. We believe this comprehensive review of MRE technique detailed above provides a state-of-the-art foundation for developing and optimizing an MRE protocol at your institution.

REFERENCES

1. Loftus EV. Update on the incidence and prevalence of inflammatory bowel disease in the United States. *Gastroenterol Hepatol (N Y)*. 2016;12:704–707.

2. Stowe SP, Redmond SR, Stormont JM, et al. An epidemiologic study of inflammatory bowel disease in Rochester, New York. Hospital incidence. *Gastroenterology*. 1990;98:104–110.

3. ACR-SAR-SPR Practice Parameter for the Performance of Magnetic Resonance (MR) Enterography 2015 (Resolution 9). American College of Radiology.

4. Grand DJ, Guglielmo FF, Al-Hawary MM. MR enterography in Crohn's disease: current consensus on optimal imaging technique and future advances from the SAR Crohn's disease-focused panel. *Abdom Imaging*. 2015;40:953–964.

5. Costa-Silva L, Brandão AC. MR enterography for the assessment of small bowel diseases. *Magn Reson Imaging Clin N Am*. 2013;21:365–383.

6. Guglielmo FF, Roth CG, Mitchell DG. MR and CT imaging techniques of the bowel. In: *Cross-Sectional Imaging in Crohn's Disease*. Springer; 2019. 49–75.

7. Fidler JL, Guimaraes L, Einstein DM. MR imaging of the small bowel. *Radiographics*. 2009;29:1811–1825.

8. Fidler J. MR imaging of the small bowel. *Radiol Clin North Am*. 2007;45:317–331.

9. Amzallag-Bellenger E, Oudjit A, Ruiz A, et al. Effectiveness of MR enterography for the assessment of small-bowel diseases beyond Crohn disease. *Radiographics*. 2012;32:1423–1444.

10. Bruining DH, Zimmermann EM, Loftus Jr EV, et al., Society of Abdominal Radiology Crohn's Disease-Focused Panel. Consensus recommendations for evaluation, interpretation, and utilization of computed tomography and magnetic resonance enterography in patients with small bowel Crohn's disease. *Radiology*. 2018;286:776–799.

11. Masselli G, Gualdi G. MR imaging of the small bowel. *Radiology*. 2012;264:333–348.

12. Guglielmo FF, Anupindi SA, Fletcher JG, et al. Small bowel Crohn disease at CT and MR enterography: imaging atlas and glossary of terms. *Radiographics*. 2020;40(2):354–375.

13. Wnorowski AM, Guglielmo FF, Mitchell DG. How to perform and interpret cine MR enterography. *J Magn Reson Imaging*. 2015;42:1180–1189.

14. Kolbe AB, Fletcher JG, Froemming AT, et al. Evaluation of patient tolerance and small-bowel distention with a new small-bowel distending agent for enterography. *AJR Am J Roentgenol*. 2016;206:994–1002.

15. Gandhi NS, Dillman JR, Grand DJ, et al. Computed tomography and magnetic resonance enterography protocols and techniques: survey of the Society of Abdominal Radiology Crohn's Disease Disease-Focused Panel. *Abdom Radiol (NY)*. 2020;45:1011–1017.

16. Oussalah A, Laurent V, Bruot O, et al. Diffusion-weighted magnetic resonance without bowel preparation for detecting colonic inflammation in inflammatory bowel disease. *Gut*. 2010;59:1056–1065.

17. Mollard BJ, Smith EA, Dillman JR. Pediatric MR enterography: technique and approach to interpretation-how we do it. *Radiology*. 2015;274:29–43.

18. Perez M, Cuscaden C, Somers JF, et al. Easing anxiety in preparation for pediatric magnetic resonance imaging: a pilot study using animal-assisted therapy. *Pediatr Radiol*. 2019;49:1000–1009.

19. Booya F, Fletcher JG, Huprich JE, et al. Active Crohn disease: CT findings and interobserver agreement for enteric phase CT enterography. *Radiology*. 2006;241:787–795.

20. Jesuratnam-Nielsen K, Løgager VB, Rezanavaz-Gheshlagh B, et al. Plain magnetic resonance imaging as an alternative in evaluating inflammation and bowel damage in inflammatory bowel disease–a prospective comparison with conventional magnetic resonance follow-through. *Scand J Gastroenterol*. 2015;50:519–527.

21. Ippolito D, Invernizzi F, Galimberti S, et al. MR enterography with polyethylene glycol as oral contrast medium in the follow-up of patients with Crohn disease: comparison with CT enterography. *Abdom Imaging*. 2010;35:563–570.

22. Laghi A, Paolantonio P, Iafrate F, et al. MR of the small bowel with a biphasic oral contrast agent (polyethylene glycol): technical aspects and findings in patients affected by Crohn's disease. *Radiol Med*. 2003;106:18–27.

23. Maccioni F, Viscido A, Marini M, et al. MRI evaluation of Crohn's disease of the small and large bowel with the use of negative superparamagnetic oral contrast agents. *Abdom Imaging*. 2002;27:384–393.

24. Young BM, Fletcher JG, Booya F, et al. Head-to-head comparison of oral contrast agents for cross-sectional enterography. *J Comput Assist Tomogr*. 2008;32:32–38.

25. Gottumukkala RV, LaPointe A, Sargent D, et al. Comparison of three oral contrast preparations for magnetic resonance enterography in pediatric patients with known or suspected Crohn disease: a prospective randomized trial. *Pediatr Radiol*. 2019;49:889–896.

26. Negård A, Sandvik L, Berstad A, et al. MRI of the small bowel with oral contrast or nasojejunal intubation in Crohn's disease: randomized comparison of patient acceptance. *Scand J Gastroenterol*. 2008;43:44–51.

27. Negaard A, Paulsen V, Sandvik L, et al. A prospective randomized comparison between two MRI studies of the small bowel in Crohn's disease, the oral contrast method and MR enteroclysis. *Eur Radiol*. 2007;17:2294–2301.

28. Makanyanga J, Punwani S, Taylor SA. Assessment of wall inflammation and fibrosis in Crohn's disease: value of T1-weighted gadolinium-enhanced MR imaging. *Abdom Imaging*. 2012;37:933–943.

29. Maccioni F, Viscido A, Broglia L, et al. Evaluation of Crohn disease activity with magnetic resonance imaging. *Abdom Imaging*. 2000;25:219–228.

30. Koh DM, Miao Y, Chinn RJ, et al. MR imaging evaluation of the activity of Crohn's disease. *AJR Am J Roentgenol*. 2001;177:1325–1332.

31. Sempere GAJ, Martinez Sanjuan V, Medina Chulia E. MRI Evaluation of Inflammatory Activity in Crohn's Disease. *Am J Roentgenol*. 2005;184:1829–1835.

32. Guglielmo FF, Kania LM, Ahmad HM, et al. Interpreting body MRI cases: what you need to know to get started. *Abdom Radiol (NY)*. 2016;41:2248–2269.

33. Davenport M. ACR Manual On Contrast Media—2020. 2020. Available at: https://www.acr.org/-/media/ACR/Files/Clinical-Resources/Contrast_Media.pdf. Accessed July 1, 2020.

34. Zappa M, Stefanescu C, Cazals-Hatem D, et al. Which magnetic resonance imaging findings accurately evaluate inflammation in small bowel Crohn's disease? A retrospective comparison with surgical pathologic analysis. *Inflamm Bowel Dis*. 2011;17:984–993.

35. Seo N, Park SH, Kim KJ, et al. MR enterography for the evaluation of small-bowel inflammation in Crohn disease by using diffusion-weighted imaging without intravenous contrast material: a prospective noninferiority study. *Radiology*. 2016;278:762–772.

36. Grand DJ, Beland MD, Machan JT, et al. Detection of Crohn's disease: comparison of CT and MR enterography without anti-peristaltic agents performed on the same day. *Eur J Radiol*. 2012;81:1735–1741.

37. Taylor SA, Avni F, Cronin CG, et al. The first joint ESGAR/ESPR consensus statement on the technical performance of cross-sectional small bowel and colonic imaging. *Eur Radiol*. 2017;27:2570–2582.

38. Dillman JR, Smith EA, Khalatbari S, et al. I.v. glucagon use in pediatric MR enterography: effect on image quality, length of examination, and patient tolerance. *AJR Am J Roentgenol*. 2013;201:185–189.

39. Cronin CG, Dowd G, Mhuircheartaigh JN, et al. Hypotonic MR duodenography with water ingestion alone: feasibility and technique. *Eur Radiol*. 2009;19:1731–1735.

40. Gutzeit A, Binkert CA, Koh DM, et al. Evaluation of the anti-peristaltic effect of glucagon and hyoscine on the small bowel: comparison of intravenous and intramuscular drug administration. *Eur Radiol*. 2012;22:1186–1194.

41. Froehlich JM, Daenzer M, Von Weymarn C, et al. Aperistaltic effect of hyoscine N-butylbromide versus glucagon on the small bowel assessed by magnetic resonance imaging. *Eur Radiol*. 2009;19:1387–1393.

42. Park SH, Huh J, Lee SS, et al. Diffusion-weighted MR enterography for evaluating Crohn's disease: effect of anti-peristaltic agent on the diagnosis of bowel inflammation. *Eur Radiol*. 2017;27:2554–2562.

43. Rao A, Sitheeque F, Gustafson S, et al. MR enterography—impact on image quality between single- versus split-dose Buscopan. *J Med Imaging Radiat Oncol*. 2020;64:331–337.

44. Grand DJ, Beland M, Harris A. Magnetic resonance enterography. *Radiol Clin North Am*. 2013;51:99–112.

45. Dyde R, Chapman AH, Gale R, et al. Precautions to be taken by radiologists and radiographers when prescribing hyoscine-N-butylbromide. *Clin Radiol*. 2008;63:739–743.

46. Ghobrial PM, Neuberger I, Guglielmo FF, et al. Cine MR enterography grading of small bowel peristalsis: evaluation of the antiperistaltic effectiveness of sublingual hyoscyamine sulfate. *Acad Radiol*. 2014;21:86–91.

47. Masselli G, De Vincentiis C, Aloi M, et al. Detection of Crohn's disease with diffusion images versus contrast-enhanced images in pediatric using MR enterography with histopathological correlation. *Radiol Med*. 2019;124:1306–1314.

48. Park SH. DWI at MR Enterography for Evaluating Bowel Inflammation in Crohn Disease. *AJR Am J Roentgenol*. 2016;207:40–48.

49. Soydan L, Demir AA, Ozer S, et al. Can MR enterography and diffusion-weighted imaging predict disease activity assessed by simple endoscopic score for Crohn's disease? *J Belg Soc Radiol*. 2019;103:10.

50. Rimola J, Planell N, Rodríguez S, et al. Characterization of inflammation and fibrosis in Crohn's disease lesions by magnetic resonance imaging. *Am J Gastroenterol*. 2015;110:432–440.