MR IMAGING OF THE BOWEL

ARTICLE TITLE

Chapter 2. MR of the small bowel: How to do it

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KEYWORDS

Enterography, small bowel, MRI, technique, protocol, preparation, guideline.

KEY POINTS

1. Small bowel MRI has been used in routine practice for nearly two decades
2. Implemented protocols still vary in patient preparation, enteric contrast and MRI acquisition sequences resulting in heterogenous diagnostic quality.
3. Consensus statements from the USA and Europe have recently been published to inform evidence-based small bowel MRI technique.
4. This chapter summarizes this guidance in addition to providing the authors' recommendations from their own clinical practice.

SYNOPSIS

Small bowel MRI has been clinically implemented for many years, albeit with variation in study technique. Considerable research has been carried out during this time regarding optimum patient preparation, choice of enteric contrast medium and MRI sequence protocol but findings have not been universally implemented. Recently however, evidence-based consensus statements have been published from the US and Europe. This chapter summarizes key findings from this guidance and presents practice examples from the authors' own institution.

Introduction

Dedicated small bowel evaluation with MRI has been in routine use for nearly two decades [1]. Once MRI technology advanced sufficiently to enable rapid acquisition of abdominopelvic sequences minimizing motion artefacts from peristalsis and respiration, it naturally followed that dedicated protocols to interrogate the small bowel would be performed following enteric distention with contrast medium, either administered orally (enterography) or via a nasoenteric tube (enteroclysis). As the technique evolved, many units adapted their existing abdominal imaging protocols for small bowel MRI, using differing bowel preparations and acquisition parameters. Consequently, heterogeneity developed in terms of institutional protocols with resulting variability in the diagnostic quality of the studies obtained. Recently however, well-researched consensus statements have emerged from North America[2] and Europe[3] providing evidence-based guidance on optimal small bowel MRI technique [TABLE 1]. While a detailed description of respective methodologies is beyond the scope of this Chapter, both groups assembled panels of expert contributors and performed systematic reviews of the available literature to develop a comprehensive set of consensus recommendations. Therefore, the purpose of this Chapter is to present available research relating to optimum small bowel MRI technique, to summarize the relevant US and European consensus guidance and to share experience from the authors' daily practice.

General patient preparation and basic MRI technique

The aim of pre-test preparation is to achieve maximal small bowel distension with enteric contrast medium while minimizing the artefacts that result from peristalsis or excessive luminal gas through use of spasmolysis and fasting.

ENTERIC CONTRAST ADMINISTRATION

Pre-test preparation

While many consider that fasting for 4-6 hours improves tolerance of oral contrast medium, there is no strong supportive evidence. Indeed, fasting for 2 to 4 hours may be sufficient[2]. Nonetheless, it is universally accepted that patients should continue their regular oral medication and avoid ingestion of carbonated drinks due to the risk of producing intraluminal gas artefacts. Clear fluids are generally thought to be acceptable; we find that a 4-hour solid food fast improves oral contrast ingestion and image quality while remaining well tolerated.

Enteric contrast medium

There is good evidence that the accuracy of MRI is improved by administration of oral contrast [4] and this is currently considered the standard of care recommended by both US[2] and European [3] consensus guidance [FIG1]. Collapsed bowel can both hide and mimic small bowel disease.

Choice of contrast agent

Ideal enteric contrast media should maximize luminal distension along the entire small bowel for the duration of the study. Water is generally insufficient. Hyperosmolar agents reduce gut absorption and viscous fluids tend to promote distension. While 'dark lumen' imaging using superparamagnetic iron oxide nanoparticles [FIG2] is favored by a few centers [5], use of media that produce characteristic luminal T2-hyperintensisty to achieve maximum contrast against the bowel wall [FIG3] is now almost universal. Such agents are hypointense to the bowel wall on T1-weighted sequences such that bowel wall enhancement is readily appreciated [6-8][FIG4]. Consequently, several oral contrast agents have been tested and their resulting properties described in

the literature [5, 9-13], yet no strong evidence from patient cohorts supports one particular agent over another. Nevertheless, a consistent finding is that distension is improved by hyperosmolar agents [13, 14] particularly when ingested between 45-60 minutes prior to the examination [8].

Commonly utilized T2-hyperintense contrast media include polyethylene glycol (PEG) and mannitol solution in varying concentrations, often prepared locally with or without bulking agents such as locust bean or xanthan gum. In the US, 0.1% low density barium sulphate suspension is also commonly administered [2]. Available SPIO contrast agents are proprietary formulations subject to local regulatory approval and much less frequently used [5, 11]. The European consensus statement states that given the lack of evidence suggesting superiority of one preparation over another, the decision is left to clinician preference. In our practice, we find a simple 2.5% mannitol solution offers reproducible signal characteristics, luminal transit and distension without compromising patient acceptability, cost or safety. In addition, we have seen that refrigeration and flavoring, for example with blackcurrant cordial, enhances compliance, particularly in children. It should be remembered that hyperosmolar agents often cause abdominal bloating and diarrhea, which are often identified by patients as the worst part of the examination[15]. Patients should therefore be appropriately counselled about such side effects and given advice on symptom management, post examination travel etc.

Contrast volume and timing

Limited evidence relates to optimal enteric contrast volume. For example, a study of 10 healthy volunteers showed volumes of less than 1000ml resulted in inferior distension[12] while others have shown that reasonable quality examinations can be obtained with as little as 450ml of oral contrast media [16]. Consequently, neither US nor European panels reached consensus on the minimum acceptable enteric oral contrast volume; in clinical practice this is usually judged on a case by case basis. Similarly, scant evidence exists for the optimal duration of enteric contrast ingestion and whether to split into divided doses or drink continuously. We aim to administer 1600ml of 2.5% mannitol solution over one hour for routine small bowel studies and 1000ml over 45 minutes where there has been extensive prior small bowel resection. It is imperative that the need for consumption of oral contrast is explained to patients and advice given on the methods of ingestion over the pre-examination time period. In our experience, such counselling improves the quality of examinations. Where an ileostomy is present, plugging is recommended by European guidance to improve enteric distension. However, there is no direct evidence to support this approach and for pragmatic reasons we do not routinely do this.

Use of rectal enema

Although there is some evidence that use of rectal contrast administration may assist in demonstration of the ileocecal junction[6] this is not recommended. Specific colonic evaluation as part of small bowel MRI protocols is discussed in further detail below.

ENTEROCLYSIS

Enteroclysis aims to achieve optimal luminal distension via direct administration of enteric contrast into the jejunum via a nasojejunal tube [17, 18]. Some studies have shown improved small-bowel distension compared to routine oral contrast administration [18] but a meaningful impact on clinical decision making has not been demonstrated [19]. Furthermore, as enteroclysis requires placement of a nasoenteric feeding tube, usually under fluoroscopic control, it is invasive and hence potential improvement in technical quality must be weighed against impact on compliance and radiation exposure.

The optimal volume of enteric contrast for MR enteroclysis should be based on real time monitoring; delivery via an automated pump system is preferred but not mandatory. In all other respects, international guidance essentially mirrors that of MR enterography for patient preparation, positioning and acquisition protocol. Overall, while acknowledging this technique can be valuable, for example to demonstrate adhesions or luminal filling defects such as polyps, enteroclysis is not considered necessary for effective small bowel MRI in inflammatory bowel disease by either US or European consensus guidance.

Technical considerations and sequence selection

PATIENT POSITIONING

Although some data suggest superior luminal distension can be achieved when prone [20], and that prone positioning may decrease coronal sequence acquisition time by compressing the abdomen, there is no hard evidence this improves diagnostic accuracy[20]. Moreover, some patients find this position difficult, particularly those with a stoma, hence supine positioning is also considered perfectly acceptable. In our practice, we attempt prone imaging wherever possible as we observer fewer respiratory motion artefacts and improved acceptability for those who find MRI claustrophobic.

SPASMOLYSIS

While some studies have suggested satisfactory small bowel MRI can be achieved without the use of a spasmolytic [21], many show significantly superior distension with the use of these agents [22], particularly proximally. Furthermore, reduction in peristalsis-related motion artefact improves study quality. International guidance therefore recommends spasmolysis prior to MR enterography. The evidence suggests both glucagon and hyoscine butylbromide are acceptable, albeit with differing onset and duration of effect. Both are most effective when given intravenously [23].

While data from healthy volunteers suggests glucagon is superior to hyoscine butylbromide for achieving complete aperistalsis [24], there is currently no evidence that this improves diagnostic accuracy. Therefore, based on expert opinion, cost and availability, in Europe, 20mg hyoscine butylbromide is recommended as the first line spasmlotyic, with 1mg glucagon as second line. Either a single or a split dose are acceptable. In the US, where regulatory approval differs, intravenous glucagon is considered first line [25]. Due to the relatively short half-life, spasmlotyics should be administered directly prior to the motion-sensitive sequences such as the T2 weighted imaging and 3D T1-weighted post-contrast series (post contrast enhanced images are particularly sensitive to peristaltic motion artefact). Intramuscular administration can also be considered if necessary; it is

longer-lasting but less predictable[23]. Naturally, both EU and US guidance mandate evaluation for contraindications or drug interactions prior to antispasmodic and contrast administration.

MRI ACQUISITION

Hardware

There is currently no EU or US consensus regarding optimal field strength for small bowel MRI; available evidence confirms high quality acquisitions are possible at both 3T and 1.5T [26, 27]. The use of phased-array coils is recommended regardless of field strength. We routinely perform enterography at both field strengths, using an extra-large torso coil, with slight parameter modifications as detailed in Table 2 and Table 3.

Essential sequences

Basic considerations

As with routine abdominopelvic studies, multiplanar imaging is recommended. Coronal plane imaging, in addition to routine axial sequences, is considered essential to small bowel MRI; it is mandated by European and US guidance. Suggested maximal slice thicknesses are 5mm for T2-weighted imaging and 3mm for 3D T1-weighted sequences. Both European and US guidelines currently recommend a basic set of acquisition sequences (balanced steady state free precession gradient echo [SSFPGR], T2 weighted images, [with and without fat saturation], and T1 weighted sequences pre and post gadolinium enhancement), together with useful but optional sequences (notably diffusion weighted imaging and cine motility).

T2 Weighted imaging

T2-weighted imaging (with and without fat suppression) is considered the cornerstone of small bowel MRI, in particular to evaluate active inflammation. Identifying mural edema is fundamental to assessing disease activity and best judged on fluid-sensitive T2-weighted sequences [FIG5]. Homogenous fat suppression may be accomplished by various techniques, including chemically selective fat saturation, Dixon-based methods, short tau inversion recovery (STIR), and spectral adiabatic inversion recovery (SPAIR) [28] although not all methods lend themselves to the rapid sequence acquisition times required for abdominopelvic imaging. Similarly, because peristalsis-mediated artefacts are not mitigated by breath-holding or respiratory triggering techniques, motion insensitive 'single shot' techniques are considered the most reliable. There is no available evidence regarding the optimal combination of regular fast spin echo T2-weighted and SSFPGR sequences, with many published studies utilizing both. SSFPGR sequences are relatively insensitive to motion artifacts and

provide clear definition of the bowel wall and mesenteric structures such as vessels and lymph nodes; we use them routinely in our practice. They are also frequently used in cine motility imaging (see below).

T1-weighted sequences

Gradient-echo and fast spin-echo techniques can be used to obtain T1-weighted small bowel MRI. Three-dimensional gradient-echo sequences (3D GRE) have the advantage of rapid acquisition times that enable imaging within the duration of one breath-hold for most patients. This minimizes respiratory motion artefact, allows for dynamic contrast enhancement via rapid repeated acquisitions and is recommended by current US guidance. However, recent developments in vendor technology, such as radial 3D GRE sequences, allow free-breathing T1-weighted imaging that show promise for patients who cannot breath-hold [29, 30]. European guidance does not specify T1 parameters; we perform 3D spoiled gradient echo acquisitions.

Intravenous contrast enhancement

Intravenous gadolinium contrast enhancement is important for comprehensive abdominopelvic MRI particularly for abscesses, collections and fistulae. Furthermore, postcontrast images are considered valuable for demonstrating mural inflammation, fibrosis [31-33] and loop tethering [34]. Research suggests use of post gadolinium T1-weighted images increases diagnostic accuracy [35, 36], and bowel wall enhancement is a component of some validated disease activity scores [37, 38]. Consequently, IV contrast is currently recommended by both European and US consensus guidelines with the latter stating that every attempt should be made to administer, unless contraindicated, for example by allergy or pregnancy. The optimal timing of sequences acquisition after injection can either be in the enteric or portal venous phase (45 to 70 seconds).

In our practice however, we are becoming cautious regarding using IV contrast media in view of the increasing evidence of possible neuronal retention of gadolinium [39]. This is of particular concern due to the generally young age of the imaged patient population and need for frequent repeat imaging in those with IBD. Moreover, in our experience, diffusion weighted imaging can often provide equivalent information, albeit with a steep learning curve. Indeed, there is increasing evidence that diagnostic accuracy can be maintained even if gadolinium administration is omitted, particularly if DWI is performed [40, 41] (see below). Furthermore, validated MR disease activity scores do not always require assessment of post gadolinium enhanced images[42, 43]. Based

on this emerging evidence, and our own 15 year experience of interpreting MRE, in our practice, we no longer perform IV contrast enhancement in routine outpatient examinations, relying on T2-weighted sequences, DWI and cine motility sequences alone. We do, however, usually administer IV gadolinium for known penetrating disease, particularly where there is suggestion of abscess or fistula.

DWI

Although considered optional by both European and US guidelines, the use of diffusion weighted imaging (DWI) is increasingly established in small bowel MRI protocols in many institutions, with evidence supporting its role for identification and quantification of inflammation [44-49], and as a potential replacement for IV contrast enhanced sequences[50]. Improvement in diagnostic utility compared to conventional MRI sequences is yet to be fully established [51] in part explaining why it is considered optional at present by the European and US expert panels. Furthermore, specificity is at best moderate [51] with collapsed bowel and lymphoid hyperplasia frequent causes of false positive findings. If used, DWI sequences must be interpreted alongside conventional sequences to avoid misdiagnosis. Nonetheless, it is widely acknowledged that DWI may have particular place in pediatric imaging [52]; specific recommendations are provided further below. Locally, we perform DWI on all patients as part of our routine protocol using B values of 0, 50 and 600 s/mm^2. European guidelines suggested that if performed, DWI should be acquired in the axial plane, during free breathing, with a maximal slice thickness of 5mm[3] [FIG6].

Motility/ Cine sequences

Dynamic small bowel motility MRI can be achieved by performing rapid repeated slices through a single slice or region of interest [53, 54], typically using SSFPGR based sequences and usually using a slice thickness of around 6-10mm [FIG 7]. The concept is to capture real time bowel peristalsis at high temporal resolution and although acquisitions can be targeted, for example on an inflamed terminal ileum, usually data is acquired from the whole small bowel volume by sequential repeated coronal acquisitions in differing anatomical locations. Small bowel affected by IBD shows altered motility, with reduction correlated to underlying inflammatory activity[55]. Increasing evidence suggest that 'cine' imaging can improve diagnostic accuracy[56, 57], aid evaluation of disease activity [55, 58, 59] and evaluate response to treatment [60]. However, both European and US recommendations

currently consider cine motility MRI as optional. In our practice we find cine motility imaging is useful to assess the severity of inflammation and subsequent treatment response, as well as local and upstream bowel function in apparent strictures. We acquire multiple coronal thick slab cine images for all patients with the addition of deep breathing sagittal motility sequences where abdominal wall adhesions are suspected.

Magnetization transfer and T2*

Magnetization transfer[61] and T2*[62] sequences are promising for quantification of fibrosis but although supportive data is slowly emerging, it is as yet insufficient to recommend use outside of a research setting. We do not currently perform these sequences in our routine practice.

Pediatric patients: specific considerations

Although pediatric small bowel MRI technique tends to mirror that of adults [63, 64], there are important exceptions. Children are less likely to tolerate prolonged fasting or fluid restriction and, according to expert opinion, the duration should be based on the child's age in line with local practice. Similarly, doses of enteric contrast, IV gadolinium and spasmolysis vary compared to the adult population and should be calculated based on the child's weight using locally agreed formulae.

While there are data supporting the benefits of glucagon on image quality, this results in nausea for around half of pediatric patients [25, 65]. Furthermore, administration prolongs scan duration, requires cannulation and it may not be licensed locally for pediatric use. Moreover, high diagnostic accuracy can also be achieved without spasmolysis [66] and hence spasmolytic use is considered optional by consensus opinion.

While IV gadolinium remains recommended in the pediatric age group, alternative techniques including diffusion weighted and motility imaging are current research priorities due to increasing concerns surrounding some gadolinium contrast agents [39]. In general, MRI technique and sequence parameters align with adult practice.

Beyond the small bowel; colonic and extraluminal imaging

Small bowel MRI inevitably images the extraluminal solid viscera and colon, but the extent varies according to acquisition technique. For example, while the perianal tissues should be encompassed in the field of view, it is neither practical nor appropriate to perform dedicated high-resolution fistula sequences in all cases. Likewise, while it is often possible to demonstrate active colitis following small bowel preparation, modifications to routine technique are required where more detailed colonic imaging is required.

Colonic preparation for small bowel MRI

While routine use of laxatives is not recommended, there is good evidence that detection of colitis is improved with administration of a water enema after bowel preparation in comparison to evaluating the unprepared colon during small bowel MRI [6, 67-69]. An alternative approach to improve colonic evaluation is prolonged oral preparation[7]. In our practice, for individual cases where colonic evaluation is required, we use the VIGOR++ study protocol [70] comprising a total of 2400 ml 2.5% mannitol solution, in two doses: 800 ml 3 hours before the examination and 1600 ml 1 hour pre-test to achieve distension of both colonic and small bowel segments. This gives excellent distension of both large and small bowel loops but at the expense of patient experience due to the increased volume of oral contrast and subsequent gastrointestinal side effects. [FIG 8]. Nonetheless, sensitivity for early mucosal disease remains low [71].

Extraluminal assessment

A comprehensive small bowel MRI protocol typically involves multiplanar multiparametric sequences including IV contrast enhancement and diffusion weighted imaging. Therefore, it can be used to simultaneously evaluate the extraluminal structures. However, routine protocols are optimized to image the small bowel within an acceptable timeframe and consequently neither the coverage nor resolution through surrounding structures is likely sufficient for detailed assessment. For example, the cranial aspects of the liver and spleen are often excluded from the field of view to reduce the duration of breath-hold sequences and DWI may be targeted, for example, to the ileocaecal junction. Therefore, while some solid organ pathology can be demonstrated well,

this can be considered serendipitous rather than an inevitable advantage of the technique. Little overlap exists between small bowel MRI and other imaging protocols, such as MRCP, and in our experience, it is often more appropriate to perform dedicated studies on a separate occasion, unless when MRI is performed under sedation or general anesthesia. The key consideration is to communicate the limitations of the technique to the referring clinician or to recommend additional focused sequences where appropriate.

Summary

While recent European and Northern American consensus statements have been developed from comprehensive literature reviews and expert opinion, small bowel MRI technique remains variable in daily practice and there is need for continued research to expand the evidence base.

In summary, small bowel MRI should be performed following enteric contrast administration, usually ingested orally, or in specific circumstances via a fluoroscopically positioned nasojejunal tube. Several media are acceptable but hyperosmolar, viscous liquid with a hyperintense T2and hypointense T1 signal is almost universally favored. Volumes vary yet for routine adult exams, a minimum of 1L should be given over at least 45 minutes. IV spasmolysis should be administered unless contraindicated, preferably just before motion-sensitive sequences. 3T and 1.5T machines with phased-array coils are acceptable. T2-weighted sequences with and without fat suppression are the cornerstone of imaging; axial and coronal planes are advised. Intravenous contrast enhancement is currently recommended although increasingly some institutions (including the authors') are omitting this in outpatient follow up examinations, particularly if they have local expertise with diffusion weighted and cine motility imaging. Whilst DWI and cine sequences are currently considered optional, the evidence base for their use continues to grow and many centers implement one or both of these sequences routinely. While small bowel MRI includes the colon and solid viscera, the examination is optimized for the small intestine and extraluminal evaluation is often limited; good communication with referring clinicians is essential to ensure appropriate expectations from the examination.

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TABLES

TABLE 1: Summary of international consensus guidance

Patient preparation and basic technique	
Patient preparation-general	Routine medications should not be stopped (V)
	Patients should not eat any solid food for 4-6 hours (V)
	Patients should not drink fluids for 4-6 hours except non sparkling water (V)
Technique- enterography	There is no single preferred contrast agent for MRE.
	Recommended agents include mannitol, PEG, sorbitol and lactulose amongst others (III)
	The optimal volume of oral contrast is 1000-1500 mL (III)
	Ingestion time of should be 45-60 minutes (V) except when previous small bowel resection
	If there is a stoma, it should be plugged before oral contrast ingestion (V)
	Laxative bowel preparation is not recommended (V)
	Water enema or prolonged oral contrast preparation is suggested for dedicated colonic evaluation
	The volume of a water rectal enema should be based on patient tolerance
Technique-MR enteroclysis	There is no single preferred contrast agent for MR enteroclysis. Recommended agents as above
	Fluoroscopic guidance for NJ tube insertion prior to enteroclysis is mandatory (V)
	The NJ tube should be 8 to 10F (V)
	Enteric contrast infusion should be via an automated pump (V)
	The rate of contrast infusion before MR enteroclysis should be between 80 and 120 ml/min (V)
	MRI fluoroscopic monitoring of small bowel filling during MR enteroclysis is mandatory (V)
	Enteric contrast progression should be monitored on the MRI table during MR enteroclysis (V)
	The optimal volume of enteric contrast should be based on real-time monitoring (V)
MR enterography / enteroclysis technical considerations and sequence selection	
Hardware	Both 1.5 and 3 T are adequate field strengths (II)
	The use of phased-array coils is mandatory (V)
Spasmolytic agents	Spasmolytic agents are recommended (II)
	Timing of administration should account for motion-sensitive sequences (V)
	The recommended first line spasmolytic agent in Europe is 20mg IV hyoscine butylbromide (V)
	The recommended second line agent is 1mg IV Glucagon (V) (1st Line in US)
Positioning	Patients can be scanned prone or supine (III)
Recommended Sequences	Axial and coronal T2 FSE without FS
	Axial and coronal SSFPGE without FS
	Axial or coronal T2 FSE with FS

	Pre and post IV contrast enhanced 3D T1-weighted gradient echo sequence with FS
IV contrast enhancement	In known or suspected IBD, sequences should be in the enteric (45s) or portal venous phase (70s)
	For suspected chronic GI bleeding contrast-enhanced sequences is should be in the arterial (30 s), enteric (45s) or portal venous phase (70s) phase
	IV contrast media should be pump-injected with an infusion rate of 2 ml/s and a dosage of 0.1–0.2 mmol/kg (V)
Optional sequences	Cine motility and diffusion weighted imaging are suggested but not mandatory (V)
	DWI should use a free breathing technique (IV)
	DWI sequences should include b values ranging from 0 to 900 (IV)
	Maximal slice thickness for DWI should be 5 mm (V)
	Coronal diffusion-weighted sequences are not recommended (V)
	Dynamic contrast-enhanced sequences are suggested but not mandatory (V)
	Magnetization transfer sequences are not recommended (V)
Parameters	Maximal slice thickness for FSE T2W and SSFP GE sequences should be 5 mm (V)
	FSE T2W sequences may be performed in either 2D or 3D, although 2D is preferred. (V)
	Maximal slice thickness for axial and coronal T1W sequences, should be 3 mm (V)
	T1W sequences should be performed in 3D (V)
Scan coverage and duration	Coverage should include at least the small bowel, colon and perineum (V)
	Total acquisition time for should be 30 minutes or less (V)

Table adapted from Taylor et al, 2017 [3]

Final list of consensus statements (achieving agreement score of 'Strongly agree' or 'Somewhat agree' by at least 80% of panel members)

Evidence strength (Oxford Centre for Evidence Based Medicine) shown in Brackets. FSE: fast spin echo; SSFPGE: Steady state free precession gradient echo; FS: fat suppression; IBD: Inflammatory bowel disease.

Table 2: Example patient preparation protocol from the authors' institution

Patient preparation	Continue routine medications
	No solid food for 4 hours; non-sparkling water only for 4 hours
	Patient arrives 1hr pre scan
	Enteric contrast; 1600ml 2% mannitol over 40 minutes (or 2500ml in two divided doses over 3hr in specific cases where dedicated colonic imaging is indicated (see main text)
	Patient consent and suitability for IV spasmolytic and IV gadolinium contrast enhancement confirmed (if indicated)
	Patients preferably positioned prone with arms above head if possible; feet first if claustrophobic
Scanning technique	1.5 or 3 T platform with large torso phased-array coils
	Scan coverage is from diaphragm to perineum; if detailed perineal imaging is required, additional fistula protocol
	Total acquisition time is just under 30 minutes
Sequences	Sequences acquired as per Table 3 (1.5T, Siemens Avanto) and Table 4 (3T Philips Achieva)
	Additional sagittal cine sequences if adhesions are suspected
	IV gadolinium administration only in known/ suspected penetrating disease. If administered, pump-injection of 2 ml/s infusion rate, dosage of 0.1mmol/kg and images acquired at 70s

TABLE 3: Example small bowel MRI protocol for 1.5T (Siemens Avanto)

Step No	Sequence	Plane	2D/3D	ST (mm)	TR	TE	FS
1	Localizer						
2	T2 TRUFI coronal BH 4mm	Cor	2D	4	3.45	1.46	No
3	T2 TRUFI transverse BH 4mm	Ax	2D	4	3.73	1.87	No
4	T2 TRUFI coronal BH 20 measures (motility study)	Cor	2D	10	3.57	1.79	No
5	**Hyoscine Butylbromide 10mg**						
6	T2 HASTE coronal BH 4mm	Cor	2D	4	600	87	No
7	T2 HASTE coronal BH 4mm FS	Cor	2D	4	500	87	Yes
8	T2 HASTE transverse BH 4mm	Ax	2D	4	500	87	No
9	T2 HASTE transverse BH 4mm FS	Ax	2D	4	500	87	Yes
10	DWI ep2d diff 3av (b values 0, 600; three averages)	Ax	2D	5	2500	85	Yes
11	**Hyoscine Butylbromide 10mg if IV contrast indicated**						
12	T1 VIBE coronal BH FS pre-contrast	Ax	3D	3.5	3.24	1.1	Yes
13	**IV Gd contrast administration**						
14	T1 VIBE coronal FS BH Post-contrast	Cor	3D	3.5	3.24	1.1	Yes
15	T1 VIBE FS transverse BH Post-contrast	Ax	3D	3	4.89	2.39	Yes

ST: Slice thickness; VIBE: Volumetric Interpolated Breath-hold Examination; FS: Fat suppressed; Cor: Coronal; Ax: Axial; DWI; Diffusion weighted imaging; HASTE: Half Fourier Acquisition Single shot Turbo spin Echo; TRUFI: True fast imaging with steady-state free precession; TR: Repetition time; TE: Echo time.

TABLE 4: Example Small bowel MRI protocol for 3T (Philips Achieva)

Step No	Sequence	Plane	2D/3D	ST (mm)	TR	TE	FS
1	Localizer						
2	BTFE BH coronal	Cor	2D	5	2.6	1.32	No
3	BTFE 5mm coronal: 30 measures (motility study)	cor	2D	5	3.7	1.85	No
4	**Hyoscine Butylbromide 10mg**						
5	HASTE BH transverse	Ax	2D	5	1100	80	No
6	HASTE BH coronal	Cor	2D	4	1200	80	No
7	T2 FS BH transverse	Ax	2D	7	1450	70	Yes
8	T2 FS BH coronal	Cor	2D	7	1882	70	Yes
9	BFFE BH transverse	Ax	2D	7	1450	70	No
10	DWI transverse (b values – 0,50,600)	Ax	2D	4	2.3	1.13	Yes
11	**Hyoscine Butylbromide 10mg if IV contrast indicated**						
12	THRIVE pre-contrast coronal:	Cor	3D	4	2.3	1.13	Yes
13	**IV Gd contrast administration**						
14	THRIVE post-contrast coronal	Cor	3D	4	2.3	1.13	Yes
15	THRIVE post-contrast transverse	Ax	3D	4	2.2	1.09	Yes

ST: Slice thickness; THRIVE: Volumetric Interpolated Breath-hold Examination; FS: Fat suppressed; Cor: Coronal; Ax: Axial; DWI; Diffusion weighted imaging; BFFE: Balanced fast field echo; ;BTFE: balanced turbo-field-echo (BTFE); HASTE: Half Fourier Acquisition Single shot Turbo spin Echo; TR: Repetition time; TE: Echo time.

FIGURE LEGENDS

FIG 1: Luminal distension with enteric contrast media at MR enterography

(A) Axial HASTE sequence obtained at 1.5T shows distal ileal loops and caecum well distended ileal loops with T2 hyperintense oral contrast medium.

(B) Coronal HASTE imaging at 3T following spectral fat suppression demonstrates optimum distension of jejunal and ileal loops.

FIG 2: 'Dark lumen' imaging using superparamagnetic iron oxide nanoparticles

T2-weighted coronal HASTE sequence following 900ml Lumirem® (Guerbet) enteric contrast administration. Note the intermediate signal small bowel wall appears hyperintense relative to the homogenous T2 hypointense luminal content.

Images courtesy of Dr Francesca Maccioni MD, PhD. Department of Radiological Sciences, University of Rome ''Sapienza'', Policlinico Umberto I, Viale Regina Elena 324, 00161 Rome, Italy.

FIG 3: Small bowel MRI following T2-hyperintense enteric contrast media.

Coronal HASTE sequences have been obtained at 1.5T (A) without and (B) with fat suppression at the level of the ileocaecal valve. The characteristic T2-hyperintense luminal content provides optimal contrast with the adjacent bowel wall. The terminal ileum is slightly thickened with subtle loss of normal architecture but there is no mural oedema to suggest active inflammation.

FIG 4: T1-weighted imaging following intravenous contrast enhancement.

Typical T2 hyperintense enteric contrast agents are hypointense to the bowel wall on T1-weighted sequences enabling abnormal mural enhancement to be readily appreciated following intravenous contrast administration. Axial 3D gradient echo sequences allow acquisition of an entire abdominopelvic volume during a single breath-hold. The terminal ileum (arrowed) is hyper-enhancing relative to the adjacent, normal small bowel loops.

FIG 5: Fat-suppressed T2 weighted imaging for demonstrating active mural inflammation

Fat suppressed coronal HASTE imaging acquired at 3T through the ileocolonic anastomosis (arrow) shows florid T2 hyperintense submucosal oedema, luminal narrowing and loss of architecture involving a long segment of actively inflamed neo-terminal ileum.

FIG 6: Diffusion weighted imaging

Increasing evidence supports the role of DWI for identification and quantification of inflammation. In this example, axial DWI obtained at 1.5T with b-values of 0 (a) and 600 (b) shows subtle restricted diffusion

involving 6cm terminal ileum (Arrow). The highest B-value should be chosen such that the normal bowel wall should be barely conspicuous to maximise contrast with hyperintense mural pathology.

FIG 7: Dynamic small bowel motility MRI

Real time cine imaging can be achieved by performing rapid repeated acquisitions through a single slice, typically using an SSFPGR sequence with a slice thickness of 6-10mm and. For example, this coronal TRUFI sequence at the level of the ileocaecal valve (arrow) can enable evaluation of terminal ileal peristalsis.

FIG 8: Modified technique for colonic imaging with MR enterography

Where dedicated colonic evaluation is required, we perform prolonged oral contrast administration in accordance with the VIGOR++ study protocol (see text). This gives excellent distension of both large and small bowel loops but at the expense of patient experience due to the additional contrast volume and ingestion duration. In this example, contrast has reached the rectum; the sigmoid is well distended and the wall, well demonstrated.