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MR enteroclysis: technical considerations and clinical applications

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Abstract Magnetic resonance enteroclysis (MRE) is an emerging technique for the evaluation of small bowel abnormalities. Adequate luminal distention, achieved by the administration of iso-osmotic water solution through a nasojejunal catheter, in combination with ultrafast sequences, such as single-shot turbo spin echo, true fast imaging with steady precession, half-Fourier acquired single-shot turbo spin echo, and 3D fast low-angle shot, results in excellent anatomic demonstration of the small bowel. Magnetic resonance fluoroscopy can be performed during MRE examination and might be useful in studying low-grade stenosis or motility-related disorders. Magnetic resonance enteroclysis is very promising in detecting the number and extent of involved small bowel segments in patients with Crohn's disease, and in disclosing lumen narrowing and extramural manifestations and complications of the disease. Initial experience shows that MRE is very efficient in the diagnosis of small bowel tumors and can be used in the evaluation of small bowel obstruction.

Keywords MRI · Ultrafast sequences · Small bowel imaging · Crohn's disease · Small bowel obstruction

Introduction

Small bowel (SB) imaging remains a most challenging process in the domain of radiology, especially in view of an incomplete diagnostic access of endoscopic techniques available. Advances in MRI hardware and software allowed for rapid acquisition of high-resolution images of the small intestine and numerous clinical applications have been proposed [1, 2, 3]. Magnetic resonance enteroclysis (MRE) is an emerging technique for SB imaging combining the advantages of conventional enteroclysis (CE) with those of cross-sectional imaging [3, 4, 5]. It is only recently introduced in clinical practice with adequate image quality coupled by the benefits of volume challenge. Results have thus far shown that functional information provided by MR enteroclysis equals that of conventional enteroclysis [2], whereas inherent advantages of the technique include detailed morphological evaluation of the bowel wall and the mesenteries. The technical aspects, clinical applications, and limitations of MRE are summarized in this review.

MRE technique

Duodenal intubation

Duodenal intubation ensures adequate SB distention, which is considered a prerequisite for identification of early or transitional abnormalities [6]. Positioning of the nasojejunal catheter may be monitored either fluoroscopically or within the MRI unit, provided that magnet design allows for comfortable access. The MRE can be performed either in association with [7] or independently from CE [2, 3, 4, 5]. When MRE follows CE, certain adjustments in the selection of the appropriate contrast agent as well as the amount and flow rate of administration are important factors for a successful exami-

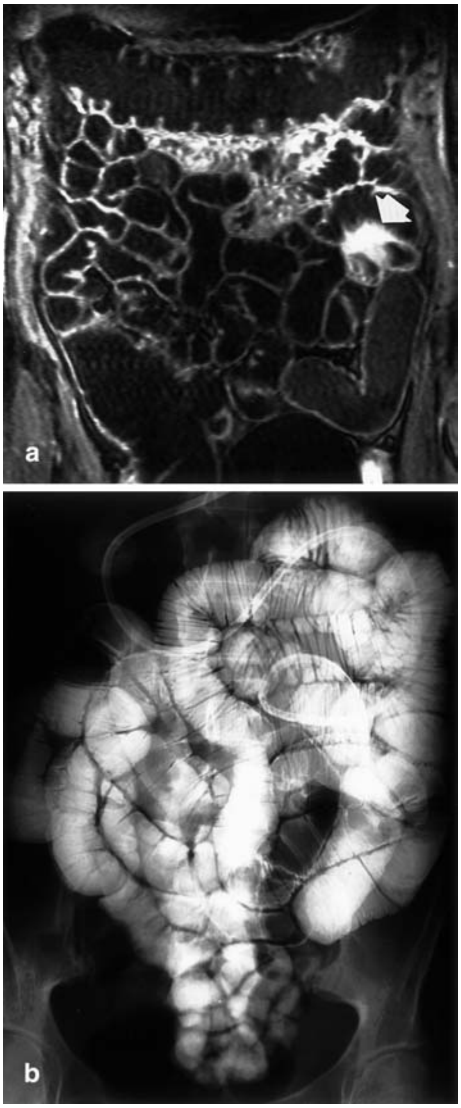

Fig. 1 **a** Coronal post-gadolinium 3D fast low-angle shot (FLASH) image with fat saturation suggesting a wall abnormality in a non-distended jejunal loop (*arrow*). **b** The corresponding conventional enteroclysis image shows no abnormality (from [15])

nation. Patient's tolerance to intubation is related to examiner's experience and it may considered as a drawback of MRE. Oral contrast administration without intubation has been proposed to reduce patient discomfort [8], but SB distention is usually not sufficient. A collapsed or not adequately distended SB loop may mask minimal abnormalities or may result in false-positive findings (Fig. 1). Recently, oral contrast agents mixed with ispaghula (Metamucil, Procter and Gamble, Phoenix, Ariz.) have been suggested [9] to distend the SB lumen without intubation, but their performance in clinical practice has not yet been evaluated. Experience has shown that a confident, detailed evaluation of small intestinal pathology requires consistently adequate luminal distention, which can be guaranteed by intubation [2, 6].

Table 1 Proposed contrast agents

Positive	Reference
Gadolinium chelates	[10]
Ferrous ammonium citrates	[18]
Manganese chloride	[19]
Food products	[20]
Negative	
OMP	[21]
BaSO4	[1]
Perflubron	[22]
Biphasic	
Water solution+mannitol	[23]
PEG	[3]

Intraluminal contrast agents

Intraluminal contrast agents are essential for lumen opacification and distention. An optimal contrast agent should provide homogeneous lumen opacification, high contrast resolution between the lumen and the bowel wall, minimal mucosal absorption, absence of artifact formation, no significant adverse effects and low cost. Numerous contrast agents have been proposed (Table 1) that can fulfill to a certain extent these criteria, but, at present, there is no consensus on the ideal one [10]. Negative intraluminal contrast agents exhibiting low signal intensity or biphasic agents provided signal intensity depending on the pulse sequence used – low on T1- and high on T2-weighted images – appear to be more suitable for SB imaging. Polyethylenglycol water solution with electrolytes (PEG; KleanPrep, Norgine, Middlesex, UK) is an iso-osmotic, biphasic contrast agent with excellent performance in MRE [3]. Through a nasojejunal catheter a total amount of 1500 to 2000 ml of the above water solution can be injected employing an MR compatible manual pump, inside the MRI suite. A controlled infusion rate is important and it should be monitored by ultrafast sequences. Initially, a flow rate of 80–120 ml/min is utilized until the contrast reaches the terminal ileum. Subsequently, the flow rate increases up to 200 ml/min to achieve reflex atony which facilitates acquisition of images with minimal motion artifacts.

Patient position

Patients can be examined either in prone or supine position; the former is suggested, to compensate for loss of ability to compress and separate bowel loops, as in CE, because it exerts mild pressure to the anterior abdominal wall thus facilitating separation of the SB loops, meanwhile decreasing the volume of the peritoneal cavity to be imaged.

Pulse sequences

A comprehensive MRE examination protocol should include both T1- and T2-weighted images, such as, for example, 3D fast low-angle shot (FLASH) and half-Fourier acquired single-shot turbo spin echo (HASTE) sequences, respectively. Incorporating different MR sequences is the most effective way to demonstrate anatomy, identify and characterize abnormalities, and to disclose associated exoenteric lesions. Sequences should be fast enough to permit breath holding and high-performance gradient systems are a prerequisite. Image quality, irrespectively of pulse sequences applied, can significantly be improved when using abdominal phased-array radiofrequency coils by increasing the signal-to-noise ratio.

Acquisition of single-shot turbo spin echo (SSTSE) images (slab thickness 7–10 cm, TR infinite, TE 1200 ms, scan time 7 s) precedes the main examination to monitor the infusion process. Projectional SSTSE images of the small bowel have been applied for demonstrating SB obstruction [2]. Faster versions of SSTSE sequence may be used for MR fluoroscopy thus providing information on SB motility.

True fast imaging with steady precession (FISP) sequence (TR 6 ms, TE 3 ms, flip angle 70°, slice thickness 4 mm, scan matrix 256 or 512, and scan time 1.5 s per slice) is a cardinal sequence for MRE. It provides motion-free high-resolution "T2-like" images of the small intestine, mesenteries, and vessels in a few seconds. True FISP source images may also be used to generate intraluminal endoscopy-like views of the SB surface. The sequence is prone to a specific type of artifacts. Susceptibility artifacts from trapped air and black boundary artifacts along to the external SB wall surface due to chemical shift phenomena may be seen (Fig. 2a); however, black-boundary artifacts can be clearly differentiated from abnormal bowel wall thickening by their low signal intensity as opposed to the moderate signal intensity of the thickened SB wall.

The HASTE sequence is used for MRE [11] providing heavily T2-weighted images with high contrast resolution in less than 1 s per slice. Imaging parameters may include TE of 90 ms, infinite TR, 4- to 6-mm slice thickness, 256×256 scan matrix, and scanning time appropriate for breath-hold acquisition of images. The HASTE images does not suffer from susceptibility or chemical shift artifacts but are prone to high-order motion artifacts usually manifested as intraluminal flow voids or blurring of SB wall edges (Fig. 2b). To overcome this limitation administration of antiperistaltic drugs, such as, for example, 1 mg of glucagon, should precede acquisition of

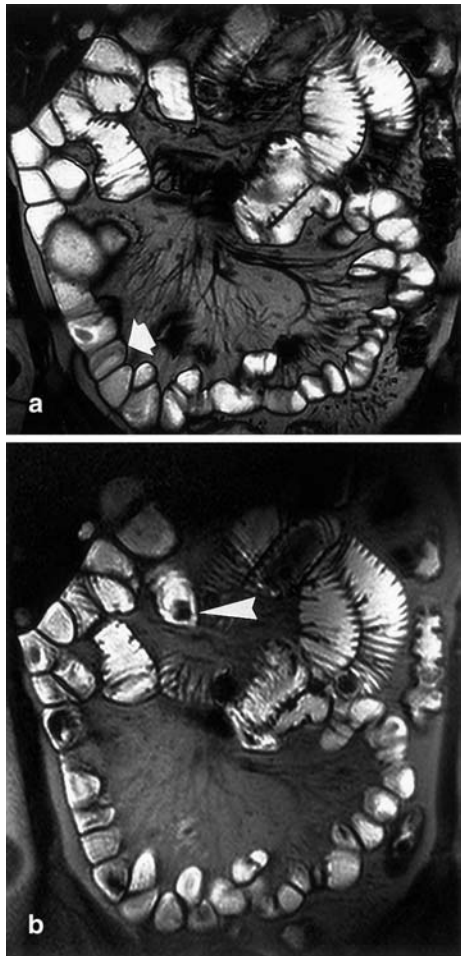

Fig. 2 **a** Coronal true fast imaging with steady precession (FISP) image and **b** the corresponding HASTE image demonstrating the normal bowel wall and valvulae conniventes in well-distended jejunal loops. Black boundary artifacts on true FISP image (*arrow*) are more pronounced at the bowel wall – mesenteric fat interface, but absent on half-Fourier acquired single-shot turbo spin echo (HASTE) image. Note the increased sensitivity of the HASTE sequence to intraluminal flow voids (*arrowhead*) compared with true FISP. The mesenteries are better demonstrated on true FISP images

HASTE images. The normal bowel wall measuring 2–3 mm in thickness is clearly seen on HASTE images with low signal intensity (Fig. 2b), as opposed to the high signal intensity of the thickened bowel wall that may be observed in patients with active Crohn's disease. The sequence is not appropriate for imaging evaluation of the mesenteries. K-space filtering effects may obscure small anatomic structures and result in decreased definition of larger vessels or lymph nodes (Fig. 2).

High spatial resolution T1-weighted images of the SB can be obtained applying a 3D FLASH sequence [12]. Fat saturation prepulses facilitate the demonstration of the bowel wall in combination with a negative intralumi-

Fig. 3 Normal appearance of jejunum and ileum on post-gadolinium 3D FLASH with fat saturation. Bowel wall conspicuity is improved by gadolinium uptake and high contrast resolution between bowel wall–intraluminal fluid and mesenteric adipose tissue

nal contrast agent. Thin sections and small pixel size allows for increased definition of the bowel wall. Intravenous gadolinium administration increases the conspicuity of the normal bowel wall and may permit lesion characterization by enhancement pattern. A 3D FLASH sequence with fat saturation may applied with 4.8 ms TR, 1.8 ms TE, 45° flip angle, 2.5-mm slice thickness, 256×512 scan matrix, and 23 s scan time. Normal bowel wall on contrast-enhanced 3D FLASH images with fat saturation exhibits high signal intensity due to gadolinium uptake and is perfectly delineated between the low signal intensity of the mesenteric fat and the negative intraluminal contrast agent (Fig. 3). A scanning delay of 60–80 s post IV contrast allows for excellent demonstration of mesenteric vessels and for disclosure of inflammatory lymph nodes. The 3D FLASH sequence is sensitive to motion; consequently, antiperistaltic drug administration should precede the application of the sequence.

A state-of-the-art MRI examination of the small intestine should comprise: adequate bowel distention; homogeneous lumen opacification; increased conspicuity of the bowel wall; demonstration of the mesenteries; information on bowel motility; ability to obtain dynamic post-contrast images; high contrast resolution and sufficient spatial resolution to evaluate subtle mucosal lesions; images free from artifacts (especially motion artifacts); and rapid acquisition times. All these virtues can be integrated into a comprehensive MRE examination protocol including small bowel intubation, administration of a biphasic contrast agent, i.e., an iso-osmotic water solution (PEG), heavily T2-weighted single-shot turbo spin echo (SSTSE) images for MR fluoroscopy and for monitoring the infusion process, T2-weighted imaging employing HASTE and true FISP sequences, and dynamic T1-weighted imaging using a post-gadolinium 3D FLASH sequence with fat suppression. This protocol can provide anatomic demonstration of the normal intestinal wall (true FISP, HASTE, 3D FLASH), identification of wall thickening or tumorous lesions (true FISP, HASTE, 3D FLASH), lesion characterization or evaluation of disease activity (3D FLASH, true FISP), assessment of exoenteric/mesenteric disease extension (true FISP, 3D FLASH), and information concerning intestinal motility (SSTSE).

The synthesis of different MR sequences, such as SSTSE, true FISP, HASTE, and gadolinium-enhanced 3D FLASH, into a comprehensive MRE imaging protocol is important to obtain all the information the method can provide in a balanced fashion, where disadvantages of one sequence are overcome by the advantages of the other. For example, susceptibility artifacts on true FISP images may prevent demonstration of a small portion of SB wall that can be evaluated on HASTE or 3D FLASH images, whereas motion artifacts downgrading image quality on 3D FLASH images do not interfere with true FISP images. Information from images obtained using different contrast mechanisms increases the confidence in lesion detection and characterization, and provides a detailed anatomic demonstration of the intestinal lumen, the wall of intestine, and the mesenteries. In addition, utilization of fast sequences make the proposed comprehensive protocol a non-time-consuming process. The average duration of the whole MRE examination within the MR unit is approximately 25 min.

Normal appearances

Excellent image quality based on homogeneous opacification and good distention of the jejunum has been achieved using duodenal intubation and true FISP sequence [3]. Wall conspicuity is excellent and the valvulae conniventes are clearly demonstrated on true FISP, HASTE, and post-gadolinium 3D FLASH sequences. Duodenal intubation can guarantee optimal distention of ileal loops, which is difficult to achieve when using per os contrast administration techniques. Adequate demonstration of the terminal ileum is essential for the evaluation of the small bowel, and it can be achieved consistently when combining true FISP sequence and duodenal intubation [3]. Normal bowel wall on MRE is uniformly thin, not exceeding 2–3 mm, and exhibits moderate signal intensity on true FISP images and high signal intensity on contrast enhanced 3D FLASH images. In addition, the demonstration of the mesenteries has become possible using the true FISP sequence: Mesenteric fat appears bright, whereas lymph nodes and vessels exhibit low signal intensity, allowing for high contrast resolution. Small lymph nodes of a few millimeters in diameter and distal vascular branches can be consistently detected without motion artifacts due to short acquisition time.

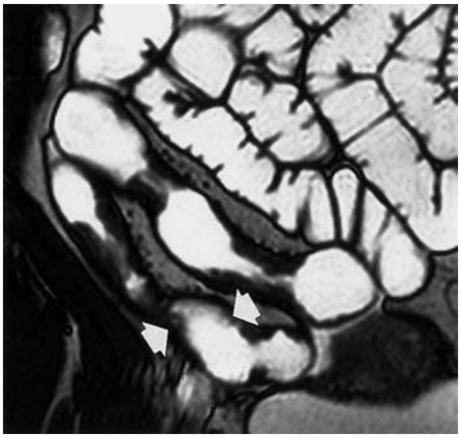

Fig. 4 Coronal true FISP section showing skip lesions in distal ileal loops in a patient with Crohn's disease. A nidus of high signal intensity intraluminal fluid surrounded by a moderated signal intensity halo is the characteristic appearance of apthous ulcers (*arrows*). (From [15])

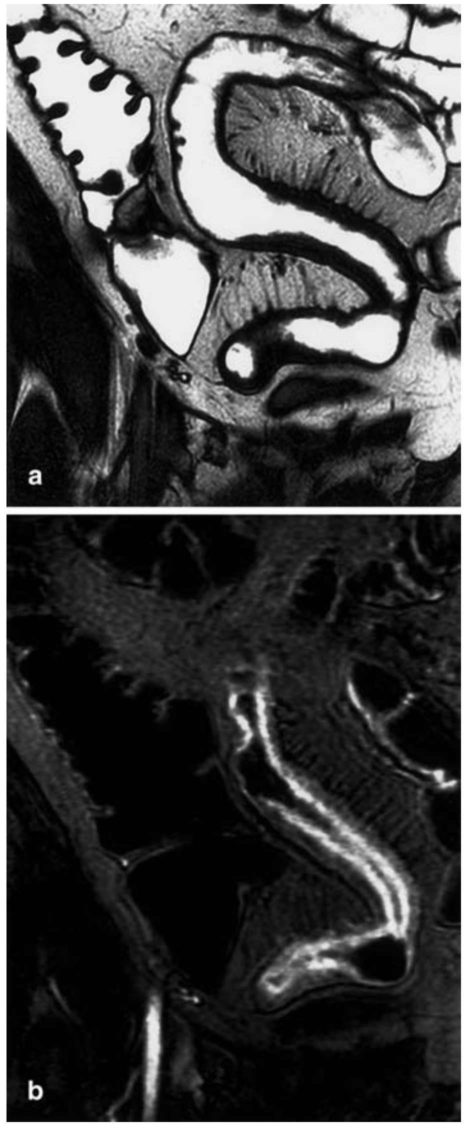

Fig. 5 Significant wall thickening and associated lumen narrowing in an ileal loop demonstrated on a coronal **a** true FISP and **b** post-gadolinium 3D FLASH T1-weighted section. Increased mesenteric vascularity (comb sign) is also visualized in **a**

Clinical applications

The most important clinical application of MRE, at present, is focused on imaging evaluation of Crohn's disease, SB tumors, and intestinal obstruction.

Crohn's disease

Magnetic resonance enteroclysis can demonstrate every abnormality from the wide spectrum of imaging findings of Crohn's disease, including early non-specific changes such as mucosal nodularity or apthous-type ulcers (Fig. 4), longitudinal or fissure ulcers, cobblestoning, intramural tracts, wall thickening (Fig. 5), luminal narrowing and prestenotic dilatation, fibrofatty proliferation (Fig. 6), mesenteric hypervascularity, the "comb sign" (Fig. 5), associated mesenteric lymphadenopathy (Fig. 7), and/or complications such as fistula formation (Fig. 8), phlegmon (Fig. 9), or abscess, and can provide pictorial evidence of disease activity.

Ulcerations, cobblestoning, and fistulas are best seen on true FISP images [5], wall thickening and luminal narrowing can be well visualized on all MRE sequences, exoenteric manifestations of the disease are demonstrated in detail on true FISP images, and complications may be more accurately diagnosed on gadolinium-enhanced 3D FLASH images with fat saturation. The latter sequence may disclose disease activity by contrast uptake in the thickened SB wall and by mesenteric lymph node enhancement. There are strong indications that disease activity can be well appreciated on MRE [13, 14], and this may represent one of the most important indications of the examination in the near future. The comb sign, corresponding to increased mesenteric vascularity, can be ideally seen on true FISP images, close to the mesenteric border of a small bowel segment in the form of short, parallel, linear structures of low signal intensity perpendicular to small bowel loop long axis [5]. The comb sign is demonstrated on 3D FLASH images as high signal intensity linear structures due to vascular enhancement. Small bowel wall contrast uptake is considered the most important indicator of disease activity [13, 14], and it can be well visualized on T1-weighted 3D FLASH images. Wall thickening, significant enhancement of the mucosa, and relatively hypointense submucosal edema have been reported as common findings on post-gadolinium FLASH

Fig. 6 Extensive fibrofatty proliferation of the ileal mesentery accompanying involved ileal segments demonstrated on a true FISP image. Small mesenteric lymph nodes with low signal intensity are also seen

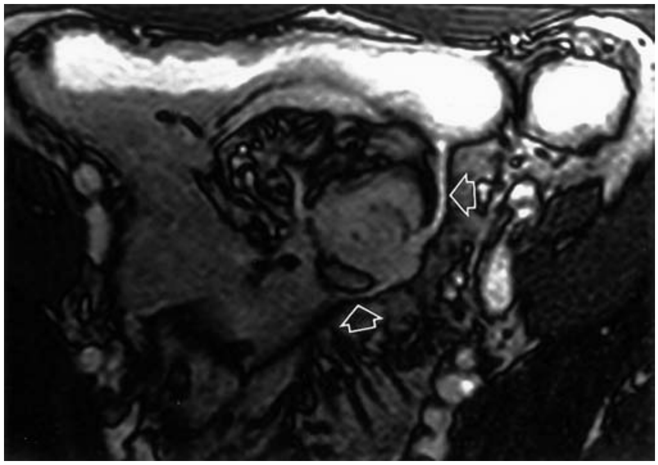

Fig. 8 Severe small bowel involvement in Crohn's disease. Multiple entero-enteric fistulas are seen on axial true FISP image (*arrows*)

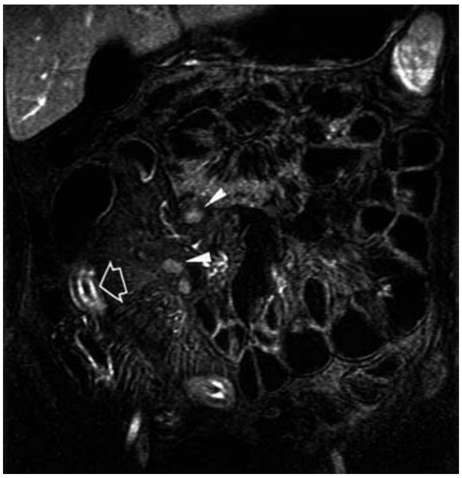

Fig. 7 Coronal 2-mm post-gadolinium 3D FLASH image with fat saturation in a patient with active Crohn's disease. Small involved mesenteric lymph nodes exhibit contrast enhancement (*arrowheads*). In addition, significant contrast uptake by the mucosa in the involved bowel loops demonstrating very high signal intensity (*arrow*) is seen. Note the weaker enhancement of the serosa and the submucosal edema. Fibrofatty proliferation separating adjacent loops is also present

images in active Crohn's disease [14]. The severity of disease process can be ranked using measurements of wall thickening, the length of the involved segment, and gadolinium uptake in comparison with renal cortex enhancement [14]. Active disease in small bowel segments may also be manifested by high signal intensity of intestinal wall on T2-weighted images [13, 15]. Intramural fat may be identified combining information from true FISP and gadolinium-enhanced 3D FLASH images with fat

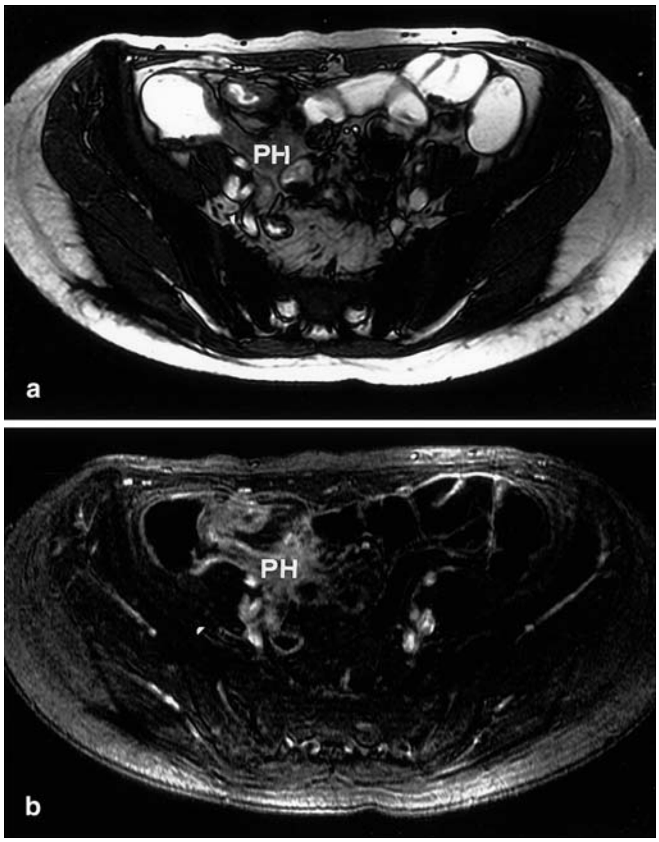

Fig. 9 A phlegmon (*PH*) is demonstrated on axial **a** true FISP and **b** post-gadolinium 3D FLASH with fat-saturation images

saturation. Discrimination between deposition of fat and presence of edema may be helpful for the disease classification.

Crohn's disease is a preferential field for the application of MRE. Different pulse sequences may offer additional information that can be integrated to provide an overall view of mucosal, mural, and extramucosal abnormalities associated with the disease and complimentary information regarding disease activity and presence of complications.

Magnetic resonance enteroclysis correlates favorably with CE in the demonstration of mucosal and mural manifestations of Crohn's disease. In our series of 42 patients MRE showed 100% sensitivity in the detection and localization of involved segments, 100% in the identification of wall thickening, 100% in the diagnosis of lumen stenosis and demonstration of associated prestenotic dilatation, 100 and 88% in the detection of SB segments with linear ulcers and superficial lesions, respectively, and 75% sensitivity in the demonstration of sinus tracts as compared with CE [5]. Magnetic resonance enteroclysis is an emerging technique for the assessment of small bowel pathology, but its clinical utility has not yet been fully established. Initial experience shows that the method is complementary to CE in detecting superficial and transmural abnormalities in Crohn's disease. In addition, MRE can provide excellent information concerning disease activity, mesenteric involvement, and complications of Crohn's disease. At present, MRE may not be suggested for the initial imaging evaluation of patients suspected for Crohn's disease, but it has a valuable and promising role for follow-up imaging evaluation of the disease and detection of its complications [15].

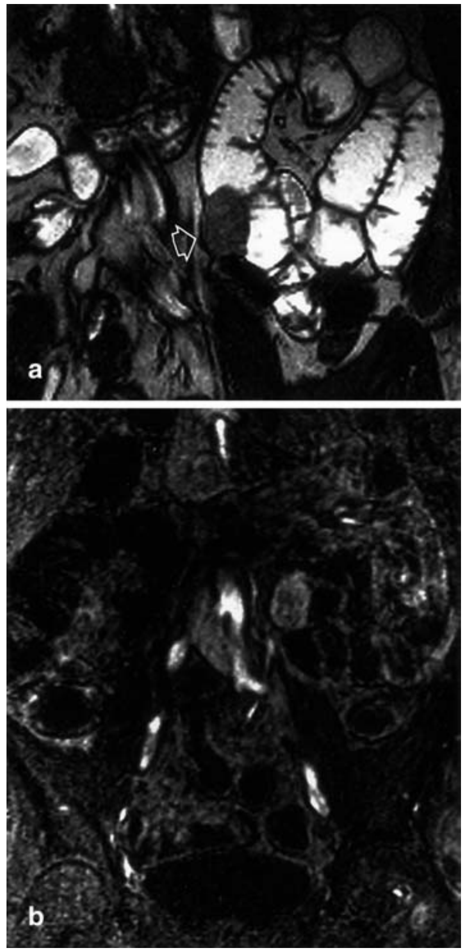

Fig. 10 **a** Coronal true FISP image demonstrating a well-defined tumor with homogeneous intermediate signal intensity corresponding to small bowel leiomyoma (*arrow*). **b** Corresponding post-gadolinium 3D FLASH coronal section demonstrating moderate inhomogeneous enhancement. (From [12])

Small bowel neoplasms

Magnetic resonance enteroclysis combines the advantages of cross-sectional MRI [16] with those of volume challenge of CE in the detection and characterization of SB neoplasms. The SB tumors usually exhibit moderate signal intensity on true FISP images (Fig. 10a), as opposed to the high signal intensity of the distended lumen and the mesenteric fat. Post-gadolinium 3D FLASH with fat saturation may be the most important sequence (Fig. 10b) for the identification and characterization of SB tumors by their enhancement pattern. The degree of prestenotic dilatation, the peritoneal extension of the neoplasm and associated lymphadenopathy is well visualized by all MRE sequences. The role of MRE in SB neoplasms has not been fully established, at present, due to the limited experience with these rare tumors.

Intestinal obstruction

Magnetic resonance enteroclysis is very effective in determining the presence and the level of small bowel obstruction (SBO) [2]. Initial evaluation of a patient with suspected SBO with dynamic SSTSE images is useful for prompt disclosure of the condition, meanwhile providing information on SB motility. In addition, MRE may reveal the cause of obstruction. Sequential true FISP images in a functional cine-MRI mode proved highly accurate in SBO due to post-surgical adhesions [17], whereas post-gadolinium 3D FLASH images may demonstrate other causes of obstruction, apart from adhesions.

Limitations of MRE

Magnetic resonance enteroclysis has not yet been adequately evaluated in comparison with other SB imaging techniques. A certain disadvantage of MRE is the limited spatial resolution as compared with conventional enteroclysis and/or multislice CT. Temporal resolution, even with functional cine-MR mode or dynamic SSTSE, is inferior to the real-time imaging provided by CE. The cost-effectiveness of the method is still under evaluation. A technically successful MRE examination and correct interpretation of its findings will also require familiarity with the application of the technique.

Conclusion

Magnetic resonance imaging has the potential to change how we evaluate the small intestine, because of its superb soft tissue contrast and functional information it can provide, its direct multiplanar capabilities, and the lack of radiation exposure. Adequate bowel distention, homogeneous lumen opacification, fast sequences with breath-hold acquisition times, both T1- and T2-weighted imaging, and contrast enhancement are cornerstones for an optimal MRI examination of the small bowel. A comprehensive MRE imaging protocol should comprise SSTSE, true FISP, HASTE, and fat-suppressed 3D FLASH sequences. Single-shot turbo spin echo is utilized for monitoring the infusion process and performing MR fluoroscopy, whereas true FISP and HASTE are used mainly for anatomic demonstration and detection of the pathology. The 3D FLASH sequences after intravenous gadolinium injection may aid tissue characterization. Inflammatory or neoplastic diseases, including intestinal wall abnormalities, exoenteric disease manifestations and complications, disease activity, and, to a lesser extent, mucosal abnormalities, can be well visualized on MRE.

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