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Review

Optimising MRI small bowel techniques

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Magnetic resonance imaging (MRI)-based techniques have emerged as the preferred technique for the diagnostic evaluation of the small intestine, particularly in the adult population. The lack of ionising radiation makes MRI ideal for use in younger patients or in cases that require repeated follow-up investigations. Imaging of the small intestine may be carried out using the intubation (enteroclysis) or the ingestion (enterography) techniques. Enterography examinations are more acceptable to patients and may provide similar diagnostic accuracy compared to intubation methods. In this review, methods of improving and optimising MRI of the small intestine are described.

Introduction

Optimal distension of the bowel lumen is one of the important factors in obtaining diagnostic small intestinal images. Distension of the intestinal lumen allows accurate evaluation of mucosal folds, mural thickness, and enhancement patterns. Intestinal segments that are not distended may hide lesions and may appear falsely thickened. Collapsed segments are also known to show abnormal enhancement patterns. Distension of the small intestine can be achieved via the enteroclysis (intubation) or enterographic (ingestion) techniques. Although naso-jejunal intubation can provide consistent distension, the procedure is technically challenging and uncomfortable for patients.[1] Furthermore, radiation is still involved during placement of the nasojejunal catheter. The enteroclysis technique is also more costly as it involves the use of the magnetic resonance imaging (MRI) and fluoroscopy suites, time, staff, and nursing support. Small prospective studies have shown no difference in the diagnostic capabilities of MR enteroclysis and MRI enterography (MRE) studies in patients with inflammatory bowel diseases (IBD). Therefore at the authors' institutions, the use of MR enteroclysis is reserved for patients in whom the MRE procedure has been sub-optimal despite a high clinical index of suspicion of small intestinal disease. Enteroclysis may also be used in patients suspected of having partial strictures that may not be highlighted with MRE examinations. This article will therefore mainly concentrate on optimisation of MR enterography techniques, as the technique of enteroclysis and its modifications are beyond its scope.

Optimising bowel distension

Distention of the small intestine depends on patient compliance, volume of contrast medium ingested, and the timing of imaging. The intake of sufficient volumes of contrast medium combined with optimal timing of image

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acquisition is paramount for achieving good-quality diagnostic images on MRE. A low-residue diet may be used prior to the MRE examination as it reduces intestinal debris and food material that may be mistaken for filling defects or lesions. Bowel cleansing or laxatives are not routinely required, as a loaded colon does not affect small intestinal transit.

Currently no consensus exists regarding the volume of contrast medium required. In a study by Kuehle *et al.*, good distension of the bowel was achieved with 1,350 ml of contrast medium and no additional benefit was achieved by increasing the volume up to 1,800 ml.[2,3] Furthermore, increasing the dose >1,500 ml causes a significant increase in side effects of abdominal cramping and diarrhoea without any additional diagnostic advantages.[2,3] A study by Lohan *et al.* reported that oral contrast medium reached the terminal ileum at a mean time of 55 minutes.[4] The optimal time for imaging the entire small bowel has been reported to range between 50–60 minutes (1,4,5). Although there is no consensus regarding the amount of contrast, most experts agree that water should not be used as an enteral agent as it does not produce optimal distension of the distal small bowel.[1,6,7] Water by itself does not provide adequate distension because of its hyposmolarity, leading to reabsorption after oral uptake. To prevent reabsorption, ingredients such as sorbitol, mannitol, or other polysaccharides need to be added to water.[6,8] Other additive agents include fibre-rich soluble polymers, such as methylcellulose, agar, and psyllium.[9] Locust bean gum, lactulose, polyethyleneglycol (PEG) and barium sulfate have also been used as enteral agents.

All these enteral agents work by retarding the resorption of water in the intestine and promoting luminal distention. MRE contrast agents may be positive, i.e., they produce increased signal intensity within the bowel lumen (gadolinium chelates), whereas negative agents cause a signal drop out (superparamagnetic particles).[10] Biphasic agents (e.g., polyethylene glycol [PEG], mannitol solution) behave as positive or negative agents depending on the imaging sequence applied. A study comparing positive and negative MRI contrast agents did not find any statistical difference in terms of diagnostic accuracy between the two agents.[11] Mannitol solution has been reported to have greater patient tolerance compared to osmotic laxative agents such as PEG or lactulose that produce more side effects such as cramping and diarrhoea.[12] Dividing the oral dose has been reported to optimise uniform, consistent distension of the intestine.[13]

Considering the available evidence regarding volume, patient acceptance, and adverse side effects, at the authors' institution, a solution of 3% mannitol in 1,200 ml is used (divided in two aliquots of 600 ml each) for MRE examinations. The patient drinks one aliquot every 25 minutes with imaging timed to commence at 55 minutes. An oral suspension of prokinetic (10 mg metoclopramide) is given with the first aliquot to promote gastric emptying. Continuous, steady ingestion of the oral contrast material over the allocated time promotes uniform and consistent filling of the proximal and distal small bowel. The most important factor for promoting intestinal transit is a full stomach.[14] Therefore the addition of a second dose of oral contrast medium keeps the stomach full, promoting peristalsis and filling of the intestine. Once oral contrast distends the terminal ileum, peristalsis and bowel transit subside due to a neuronal and hormonal feedback mechanism. As metoclopramide reaches its peak serum concentration at 20–30 minutes, its administration at the beginning of the process invigorates gastric emptying and peristalsis (of the second aliquot) by overriding the feedback mechanism. Just prior to acquiring images, patients should be given another 200 ml contrast material to outline the stomach and duodenum. If contrast medium is seen to have reached the ileocecal junction on the initial thick-slab image, intravenous injection of anti-peristaltic drugs is administered (20 mg hyoscine-N- butylbromide [Buscopan] or 1 mg glucagon) and further imaging is performed. Several studies report placing patients in the prone position during scanning, although this may be uncomfortable for patients. Furthermore, there is no substantial scientific evidence that prone scanning reduces peristalsis or provides better image quality. Therefore, at the authors' institutions, patients are preferentially scanned in the supine position.

Optimising MRI sequences

Small intestinal MRI investigations are mainly performed for diagnosis and assessment of IBD, particularly in the adult population in Europe and UK.[1,15] In children, ultrasound or capsule endoscopy may be the preferred option. Conversely, there is greater experience and use of CT in North America for the diagnosis and follow-up of IBD. Therefore, for purposes of this review, the MRI sequences will be described in relation to their usage in IBD. MRE imaging sequences are targeted towards the detection of: anatomical findings (e.g., mural thickening, ulcers, fistula, sinuses, strictures, and abscesses), pathophysiologic findings (e.g., increased enhancement of bowel, fistulae or abscesses, engorged mesenteric vessels, mural oedema) and molecular findings (e.g., abnormalities on diffusion-weighted [DW] MRI).

Steady state precession sequences

MRE is performed using ultra-fast sequences based on steady state precession such as true fast imaging with steady-state with free precession (true-FISP), balanced fast-field echo (bFFE), steady-state free precession (SSFP), or fast imaging employing steady state precession (FIESTA). These sequences need short, single breath-holds and are relatively insensitive to movement artefacts. These sequences provide high contrast between the bowel wall, lumen, and the mesentery, and are the primary sequence for evaluating the small intestine.

A significant disadvantage of these sequences is the black boundary artefact along the bowel wall (Fig 1). This artefact may mask early peri-intestinal transmural disease, sinuses, or small fistulae. It is advisable to use fat suppression to

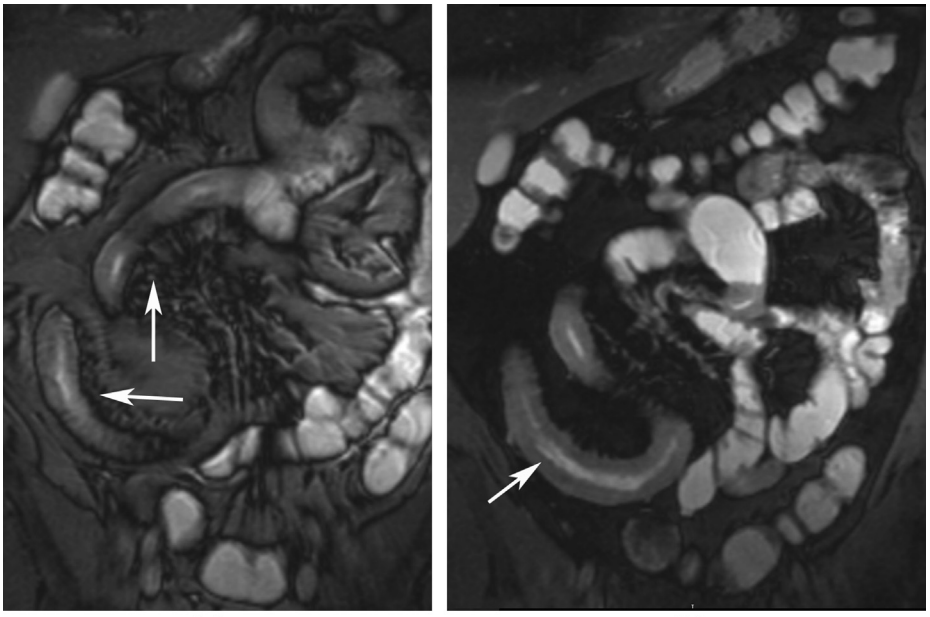

Figure 1 MRE examinations in a 36-year-old male patient. (a) Coronal True-FISP image shows black-boundary artifact adjacent to bowel wall (arrows). This artifact can obscure early mural changes. (b) Coronal True-FISP image with fat suppression reduces the artifact. High signal is seen parallel to the lumen consistent with a linear ulcer (arrow).

optimise this sequence. Broader chemical shift artefacts may be produced on higher gradient scanners (3 T) that may reduce the image quality. Fat suppression helps to minimise this chemical shift black-boundary artefact. Typically, these sequences are acquired as contiguous images, 4–6 mm in thickness and require breath-holds between 18–22 seconds.

Steady state precession sequences may be further optimised by the addition of thin-section high-resolution images. It has been reported that high-resolution, thin-section images have greater diagnostic accuracy in detection of ulcers, fistulae, and mural oedema.[16,17] High-resolution images are acquired with the imaging plane placed parallel and perpendicular to the affected intestinal segments in order to maximise visualisation of mucosal and mural abnormalities. High-resolution images are obtained with contiguous thin sections (2–3 mm), using 160–250 mm field of view (FOV) and matrix sizes of

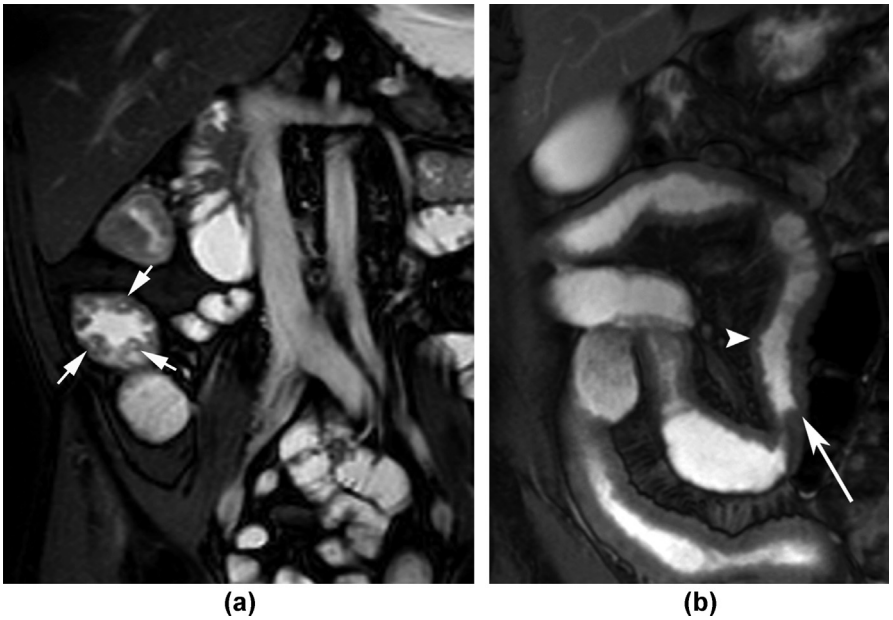

Figure 2 High resolution True-FISP images from MRE examinations. (a) Coronal image shows multiple aphthous ulcers (arrows). (b) Coronal image shows marked nodular thickening of mucosal folds with shallow (arrowhead) and deep ulcers (arrow) in CD.

128–256×128–256 that provides in-plane resolution of 1–2 mm. Images aligned parallel to the intestinal segments allow detailed visualisation of mucosal irregularities and abnormalities; whereas images aligned perpendicular to the intestine provide accurate visualisation of transmural ulcers, fistulae, and sinus tracts (Fig 2).

In a study comparing validated with matched surgical samples, the sensitivity and specificity of high-resolution MRE in the detection of superficial and deep ulcers was increased (69–99% and 94–99%, respectively) compared to standard imaging.[16] The increased accuracy is likely to be due to increased in-plane resolution, faster scanning times, and high-quality multiplanar reconstruction (MPR) images. Generally, a mural thickness of >3 mm is considered abnormal, therefore, resolution of <3 mm is best suited to detect early ulcerations. Gourtsoyiannis *et al.* ranked the

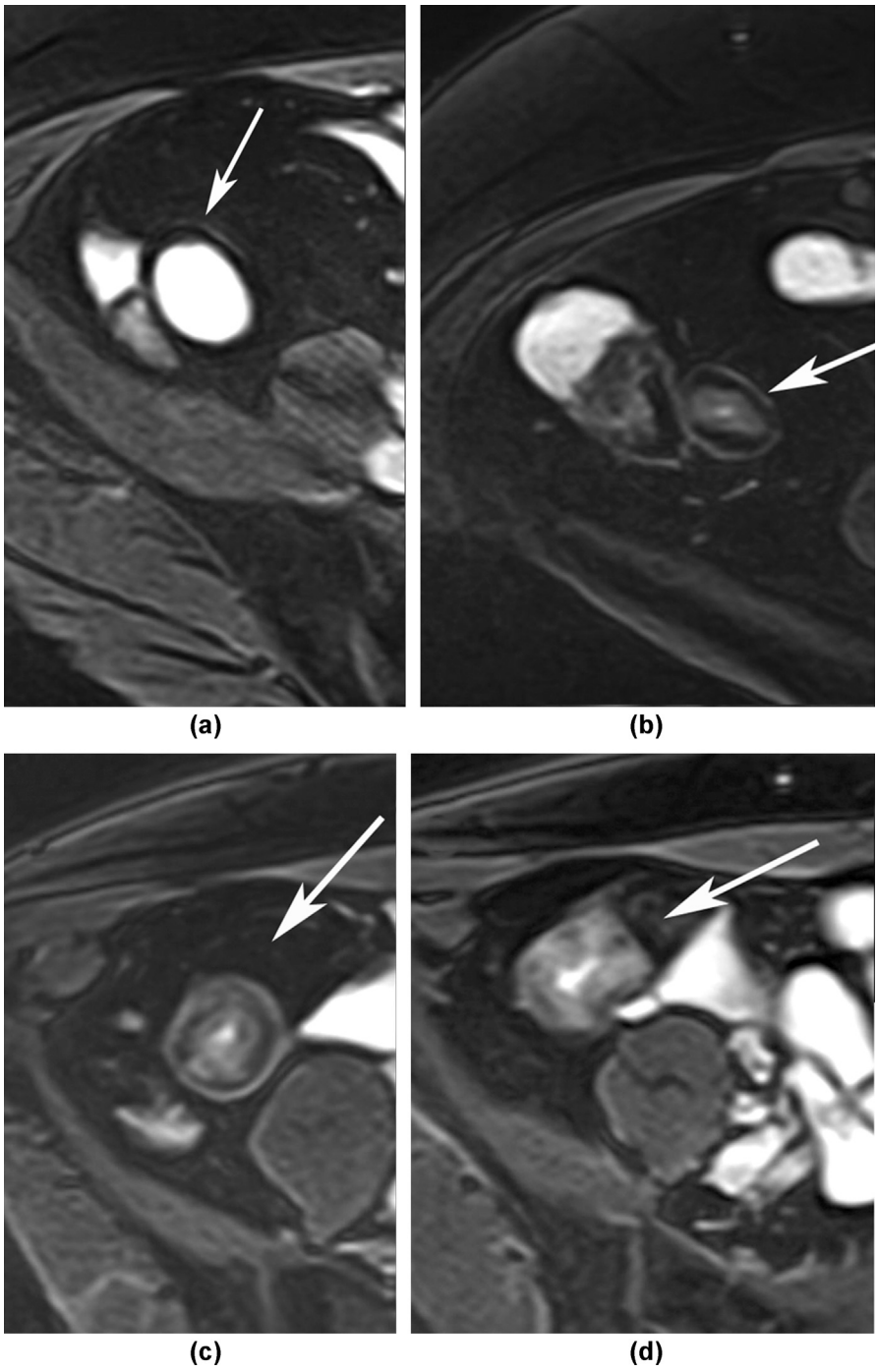

Figure 3 High resolution True-FISP images from MRE examinations in recurrent disease. (a) Quiescent CD is seen as a halo sign with hypointense submucosal layer. (b) Early recurrent mucosal inflammation presents initially as thickening of the mucosal layer (arrow). (c) Progression of mucosal thickening and isointense finger like projections in the submucosal (arrow). (d) At more advanced inflammation, the entire submucosa becomes iso- or hyperintense (arrow). Recurrence seen in figures b and c are unlikely to be detected on MEGS assessment.

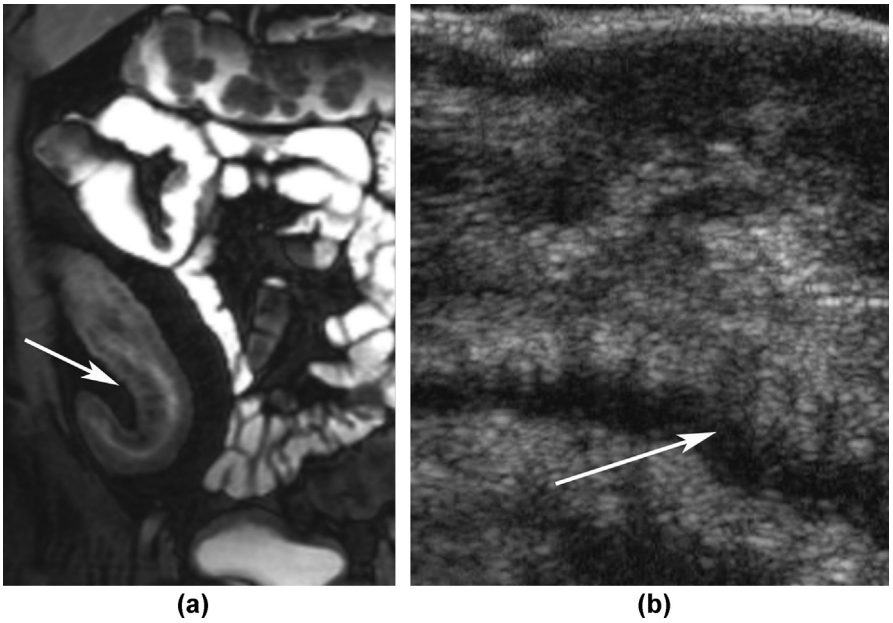

Figure 4 High resolution True-FISP images from MRE examinations in recurrent disease. (a) Recurrent mucosal inflammation shows striped appearance of the submucosa. (b) Similar appearance is seen on ultrasonography as hypoechoic linear streaks (arrow) within the echogenic submucosal layer.

product of bowel wall thickness, lymph node enhancement, and intestinal ulcers as having the strongest correlation with active Crohn's disease (CD). Therefore, optimised sequences to detect bowel ulceration are important. High-resolution images also play an important role in the detection of early recurrence in IBD.[18] The earliest feature of recurrence is demonstrated as thickening of the mucosa on background of a hypointense submucosal layer (Fig 3). Subsequently, transmural inflammatory exudates appear as irregular or linear tracks in the submucosal causing a "tiger-striped" appearance (Fig 4). Early recurrence is difficult to evaluate with MR activity scores (such as the Magnetic Resonance Enterography Global Score [MEGS]) that place dependence on mural oedema as the changes are subtle with mucosal thickening and linear changes that may not demonstrate oedema. In two reported validation studies that included patients with active bowel inflammation, one reported ulcers being visible for 71% of patients whereas the

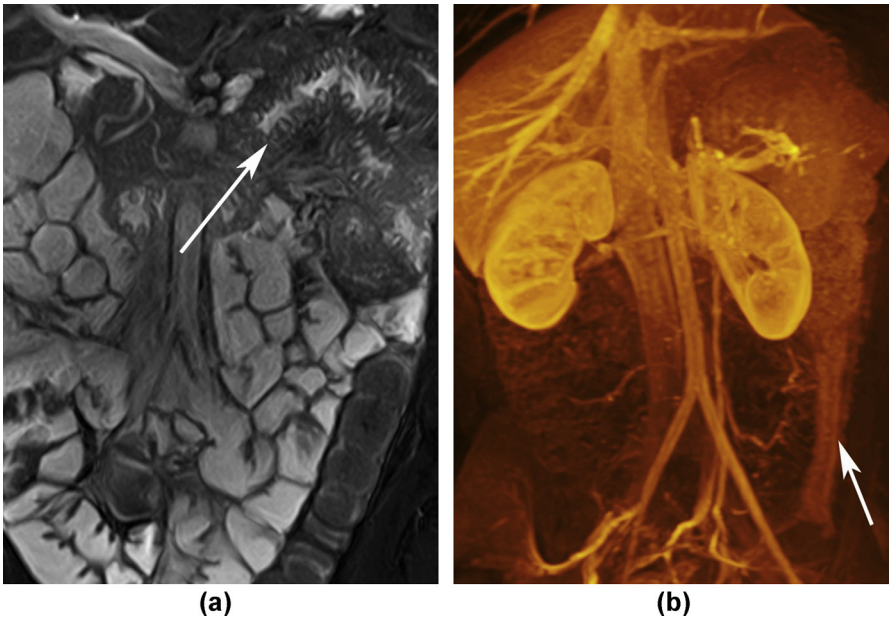

Figure 5 3-D coronal projections from MRE examinations. (a) Coronal MIP allows enhanced visualization of nodular thickening with oedema of jejunal mucosal folds (arrow). (b) Colour coded enhancement signal on MRE in a 22-year-old female patient shows hyperaemia/perfusion in the descending colon with enlarged branches of the inferior mesenteric arcade (arrow). The lumen is narrowed due to inflammation.

Table 1
Magnetic resonance (MR) enterography sequences.

MR sequences	Steady state precession sequences with fat saturation (e.g. true FISP)	High-resolution steady state precession sequences with fat saturation	Half Fourier single-shot sequences (e.g. HASTE)	Diffusion-weighted MR sequences	Contrast-enhanced 2D or 3D T1 weighted spoiled gradient echo sequences with fat suppression
Plane	Coronal and axial	Axial and coronal aligned along abnormal bowel segment	Axial	Axial free breathing Fat suppression Parallel factor 2	Coronal and axial unenhanced and enhanced (60 s after contrast medium administration)
No. of sections	19–25	12–16	15–20	25–40	52–64
Section thickness (mm)	5–6	2–3	5	5–6	2.5–3.5
Field of view (mm^2)	400×400	128–256×128–256	512×400	400–512×400–512	400×400
Repetition time (ms)	2.5–4.0	2.5–4.0	1,200	>2,500	2.5–5.12
Echo time (ms)	1.6–1.8	1.6–1.8	80	80	1–2.5
Flip angle (°)	50–80	50–80	90–140	*b*=0, 400, 800, 1,000	10–20

other noted hardly any visible ulcers at MRE.[19,20] Recognition of individual ulcers on MRE images can be difficult, although a clear delineation of individual ulcers is possible at times especially on high-resolution images.[16,21] Later in the inflammatory process, small ulcers or breaks in the mucosa are evident and there may be complete iso- or hyper-intensity of the submucosal layer. It is at this later stage that MEGS are more useful or accurate.

T2-weighted sequences

T2-weighted fast sequences, such as HASTE or SSFSE, produce high contrast between the lumen and the bowel wall and are insensitive to the black boundary artefact. These sequences may highlight mucosal fold abnormalities against the bright lumen and are also useful for detecting oedema within the intestinal wall; however, they are susceptible to motion artefacts produced by flow voids. Parallel imaging techniques should be used to reduce the data acquisition time for T2-weighted sequences by decreasing specific absorption rate (SAR), and thereby allowing greater coverage.

The use of these sequences is limited as most of the anatomical information is provided by the true-FISP sequences. The detection of mural high signal (oedema) on these sequences implies presence of mural inflammation; however, in chronic disease, the submucosa may be fibrotic and usually shows marked hypointensity, and therefore oedema may not be readily apparent. In such cases, the change in the submucosal hypointense signal (fibrosis) to iso-intensity or hyperintensity (oedema) may herald the onset of recurrent inflammation. These sequences may also be used for measuring mural thickness as the black-boundary artefact on steady state precession sequences may obviate accurate measurements.

MPR images

Thin-section MRI images should be used for three-dimensional (3D) reconstruction and MPR images for evaluation. Maximum intensity projection (MIP) uses the highest attenuation voxels in a data set and interpolates them onto an image. On the MRE examination, the highest attenuation voxels are produced by the intraluminal contrast and the vasculature. Therefore, MIP images can amplify the visualisation of subtle ulceration, mucosal fold nodularity, oedema, and strictures. It also accentuates the findings of mesenteric engorgement and hyperaemia.

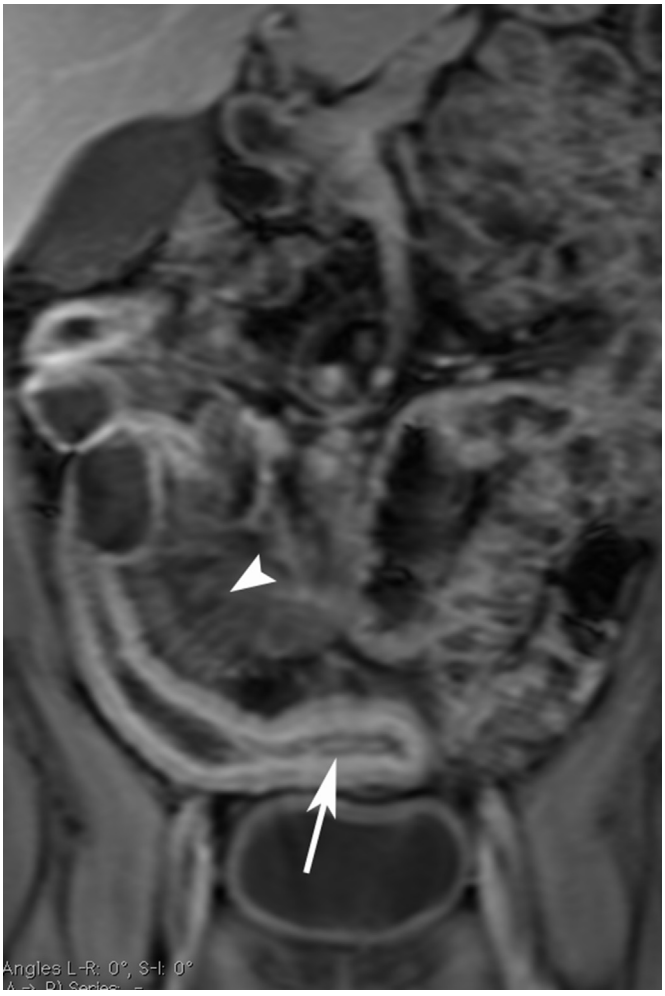

Figure 6 Post Contrast Coronal image shows marked enhancement in the inflamed bowel. Linear enhancement (arrow) indicates longitudinal ulceration.

Volume rendering (VR) assigns colour and transparency values to each voxel in a dataset based on its signal intensity and projects them on an interactive 3D display. VR accentuates the soft tissues and bowel wall thickening and enhancement. The use of MPR and 3D techniques facilitates detection of subtle abnormalities and enhances abnormal findings that are easier to visualise for the radiologist (Fig 5).

MR fluoroscopy

Initially during the MRE examination, a thick-slab HASTE image is obtained to check the progress of the contrast column at 50–55 minutes (Table 1). If bowel obstruction is observed on thick-slab HASTE images, MR fluoroscopy may be performed to assess for inflammatory adhesions or strictures prior to administration of the anti-peristaltic drugs (Buscopan). Changes in bowel peristalsis can be evaluated on MRI fluoroscopy to demonstrate either an obstructive fibrotic or inflammatory stricture.[22] MR fluoroscopy is done using true-FISP cine sequences using frame rate of 0.5–2 sections per second in the coronal or sagittal planes as required (Electronic Supplementary Material Video S1).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.crad.2019.03.007.

Contrast-enhanced images

Images obtained after intravenous contrast medium administration are acquired on T1-weighted sequences either in two or three dimensions. These sequences are commonly known as two-dimensional and 3D fast low angle shot (FLASH) or volumetric sequences such as VIBE (volumetric interpolated breath-hold examination). Fat saturation should be used to optimise contrast resolution and better evaluation of bowel enhancement.[5] As the contrast-enhanced sequences are usually the last to be performed, the effect of the anti-peristaltic agent (Buscopan) may start to fade and motion artefacts may reduce the image quality. It may be advisable to administer a second dose of the anti-peristaltic agent prior to acquiring the post-contrast images. The small bowel peak enhancement occurs slightly before the portal venous phase and the imaging sequences may have to be obtained at 50–60 seconds after the contrast medium injection.

Contrast-enhanced images are best suited to demonstrate pathophysiological changes of bowel inflammations such as hyperaemia, increased enhancement, and dilated mesenteric blood vessels (Fig 6). Increased mucosal enhancement may also be a sign of recurrent inflammation in patients being followed up for chronic IBD. In chronic CD, early recurrence may be seen as localised areas of hypervascularity, termed as serosal hypervascularity (Fig 7). Contrast-enhanced images are also very useful in differentiating between an inflammatory mass and an abscess, which may not be apparent on true-FISP or HASTE sequences (Fig 8).

Significant correlation has also been reported between histological inflammatory grade and greater enhancement (ρ=0.66).[3] Mural thickness >4.5 mms and an enhancement ratio of >1.85 have been reported to have significant correlation with advanced transmural inflammation (as opposed to minor inflammation) on MRE and contrast-enhanced ultrasound studies.[1,21,23]

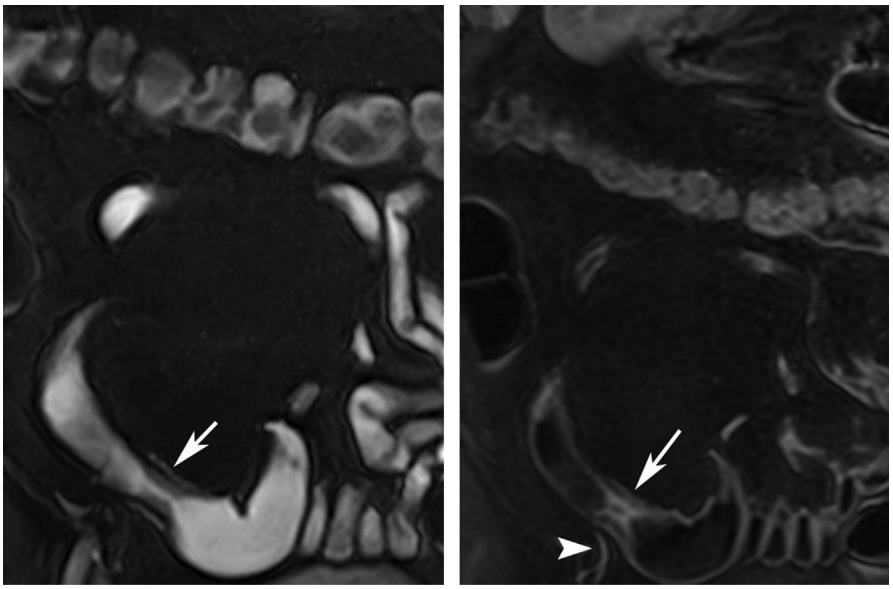

Figure 7 (a) True-FISP image shows mucosal thickening with a stricture. Note beaded appearance of the serosal surface at site of recurrence (arrow) indicative of enlarged serosal vessels. (b) Post Contrast Coronal image shows enhancement of thickened mucosa (arrow) and engorged supplying vessel (arrowhead).

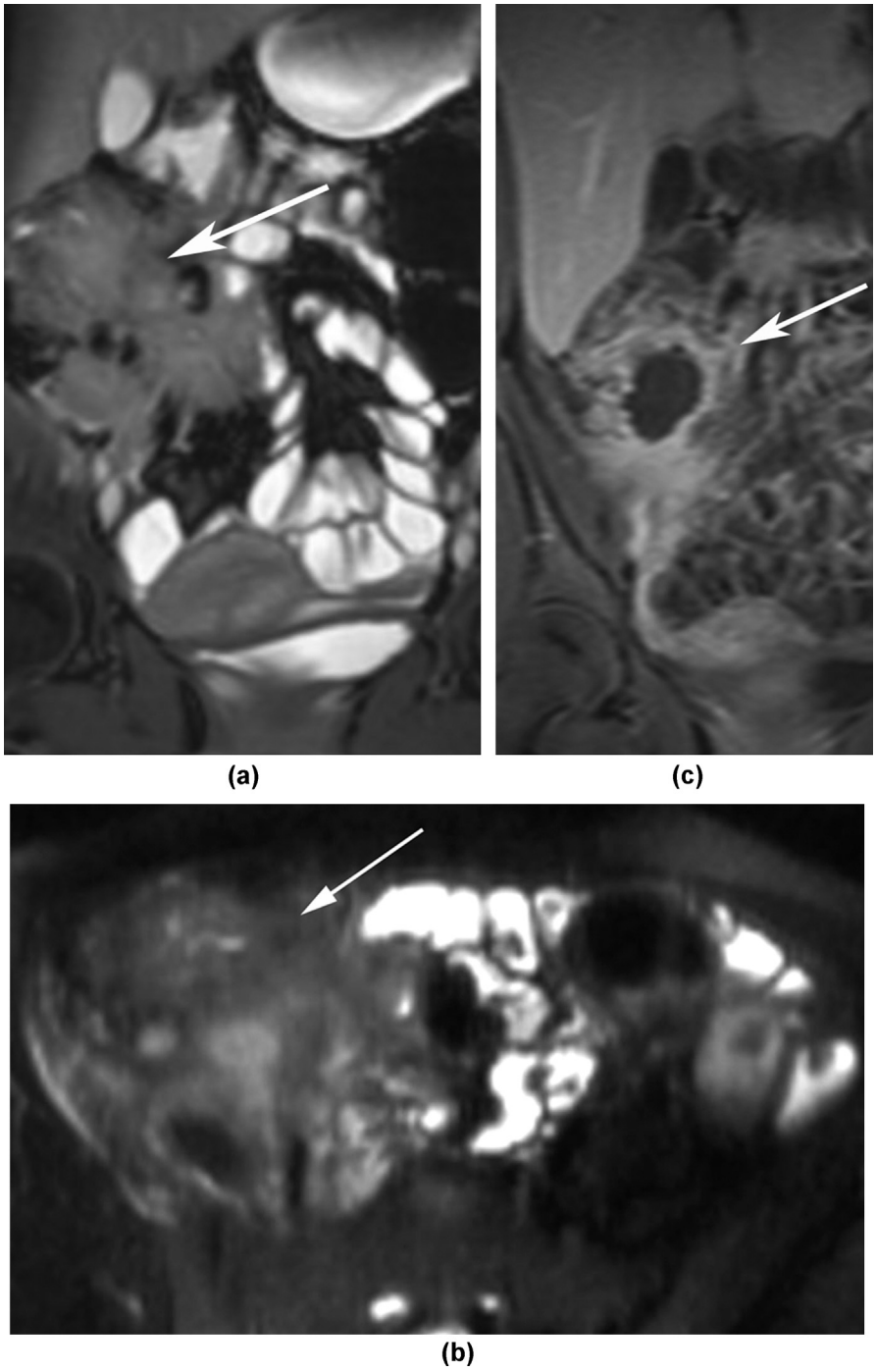

Figure 8 (a) True-FISP image shows marked ileal inflammation (arrow). (b) Axial HASTE image shows marked oedema in the ileum (arrow) with phlegmon anterior to the psoas muscle. Anatomical information is limited on the HASTE sequence. (c) Post Contrast Coronal image shows ring enhancement consistent with an abscess (arrow).

DW sequences

DW MRI signal is derived from the motion of water molecules within cells or extracellular spaces. The use of high b values (b=1,000 s/mm^2) is recommended in DW MRI of the small intestine in order to negate the high signal intensity of normal bowel mucosa and shine through effect from luminal contrast.[24] Intestinal tumours or inflammation have restricted water diffusion and show up as areas retaining high signal intensity on high b values. Studies have shown that restricted diffusion in the bowel wall correlates with the depth and severity of bowel ulcers and inflammation.[21,25]

The advantages of DW MRI are its non-invasive nature and no requirement for intravenous contrast medium. DW MRI uses the diffusion of water to produce images and therefore provides functional, quantitative information at the cellular level.

DW MRI images may be acquired by using with a breath-holding, single-shot technique or a free-breathing, multiple-averaging technique. Single-shot breath-holding sequences allow assessment of a target volume or organ and are less susceptible to motion artefacts; however, the single-shot breath-holding sequence has a poor signal-to-noise ratio (SNR) and is more sensitive to susceptibility and pulsation artefacts.[26,27] DW MRI images should be optimised by using the free-breathing technique. The free-breathing technique can be used to evaluate large areas and allows the use of multiple b values, which results in a more accurate apparent diffusion coefficient (ADC) calculation.[24,26,27] Free-breathing sequences have better SNR and a 4–6-mm section thickness that allows MPR. Images obtained with the free-breathing technique can be combined with anatomical images to yield fusion images that are spatially accurate. High b values (>800–1,000 s/mm^2) should be used to negate T2 shine-through from luminal contents and intestinal mucosa.

DW MRI images may be viewed in a linear grey scale, reversed linear grey scale, or with colour coding. Reversed grey-scale images are visually similar to nuclear scintigraphy images (e.g., bone scintigraphy) and may be more familiar to interpret for radiologists (Figs 9 and 10).

DW MRI may be particularly useful in patients in whom intravenous contrast material is contraindicated because of an allergy or renal impairment. Recently concerns have been raised regarding accumulation of gadolinium chelates in the brain in patients undergoing repeated contrast medium enhanced examinations and the use of DW MRI may be useful in these cases.[26] DW MRI can be helpful in diagnosing and quantifying pathological conditions in such patients (Fig 10). By nulling the signal from all tissues except the areas of inflammation, DW MRI may depict early recurrent mucosal disease, which demonstrates a high-signal-intensity double line, or “tram track” (Fig 10). DW MRI can be used in the follow-up of patients with IBD. Successful treatment is indicated by decreased signal

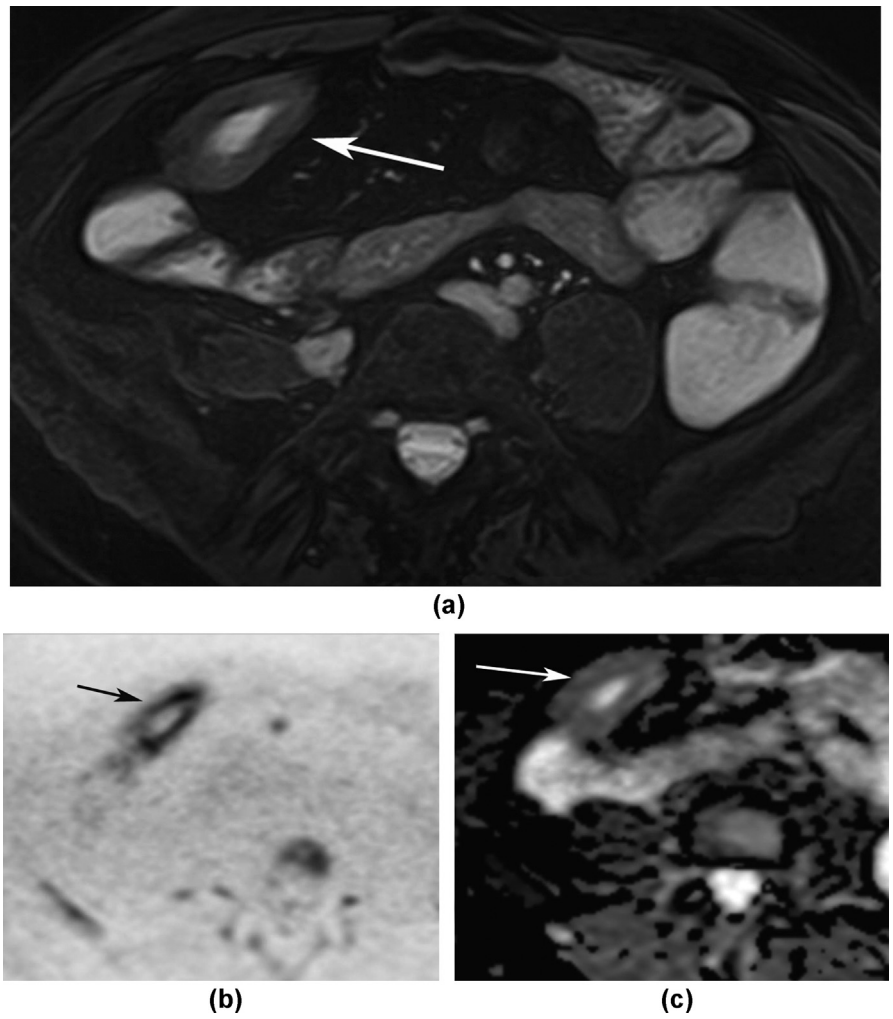

Figure 9 DW-MR imaging. (a) Axial True-FISP image in 39-year-old male patient with marked thickening and inflammation of the ileum (arrow). (b) Axial DW-MR image shows increased signal at the site of inflammation. (c) ADC map shows hypointense signal in the affected segment (arrow).

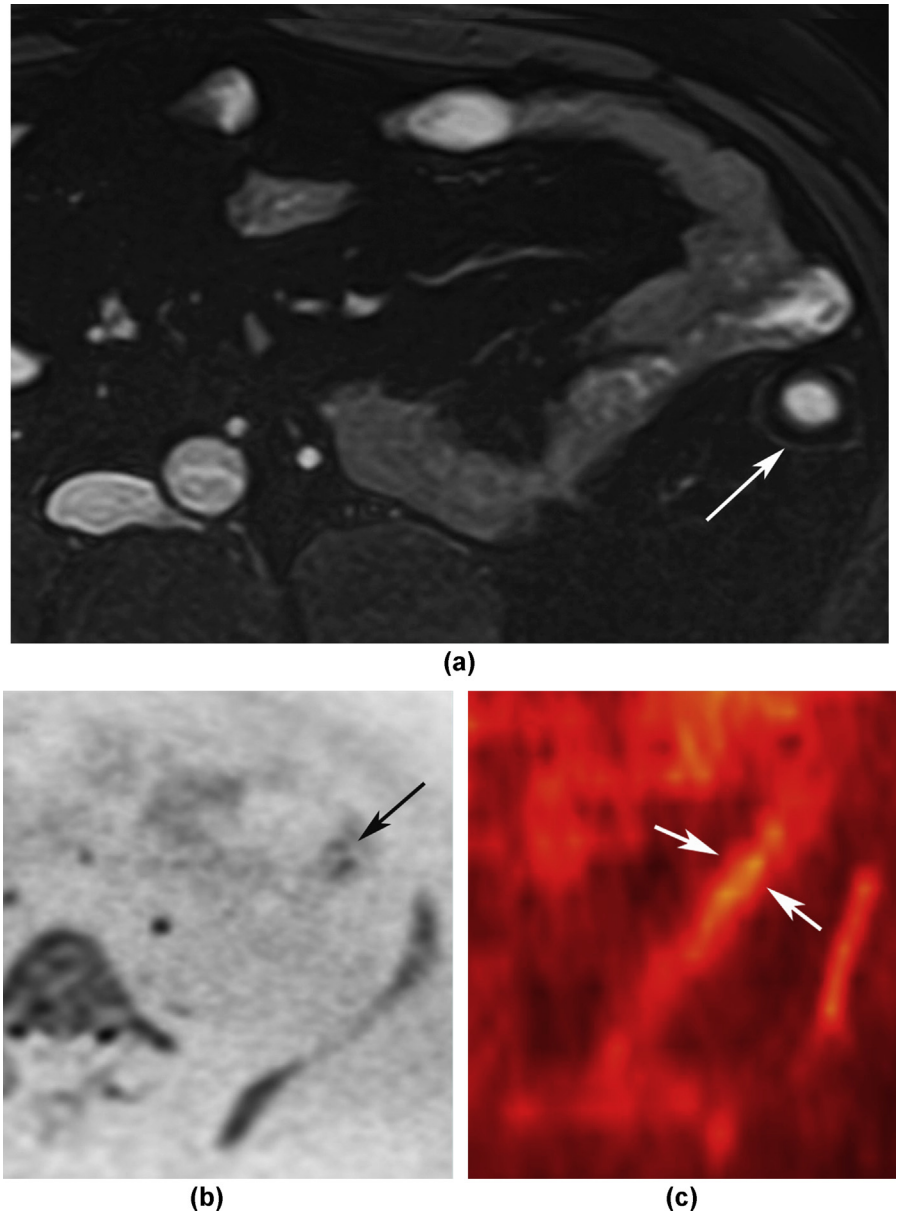

Figure 10 (a) Axial True-FISP image in 46-year-old male shows quiescent disease in the descending colon. (b) Patient could not undergo contrast injection and DW-MR image shows a 'tram-track' type high signal in the mucosa indicative of recurrent mucosal inflammation (arrow). (c) Colour coded DW-MR MPR image shows high signal in the mucosa within the thickened bowel (arrows) with greater visibility.

intensity on DW images and increased ADC values of the affected segments.

MRE scoring systems

Accurate and high-quality, optimised MRE examinations help in detecting disease activity and assessing severity as compared to pathology and colonoscopy.[28,29] Currently MRI grading systems (e.g., MEGS) are being used that show good correlation between MR scoring and ileocolonoscopy, although their use in clinical practice is very limited[19,21,30,31]; however, most of these grading systems have not been validated in large studies and another limitation is that they rely on subjective parameters (mural oedema, enhancement) that do not have any corresponding indices on histopathology. Nevertheless, using good-quality imaging with objective findings such as ulcers, mural thickening in combination with other findings may make future scoring systems even more accurate.[32]

Conclusion

Optimising luminal distension plays an important role in obtaining diagnostic images in MRI examinations of the small intestine. The application of high-resolution images, MPR and DW MRI allows greater accuracy and diagnostic sensitivity. DW MRI may also help in situation where intravenous contrast medium cannot be used. Optimising

the combination of patient preparation and appropriate MRI sequences and image display parameters therefore play a critical role in acquiring optimal diagnostic images of the small intestine.

Conflict of interest

The authors declare no conflict of interest.

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