Crohn's disease, advances in MRI
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Chapter 2

MR imaging of small and large bowel

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Introduction

The bowel is an organ which was not easily and accurately assessable until the introduction of cross sectional imaging and newer endoscopic techniques. The location, length and bowel peristalsis were major hurdles which were first overcome by the introduction of conventional radiology. Barium follow through examinations and conventional enteroclysis gave valuable information on the presence of stenoses and mucosal lesions while barium enema and double contrast barium enema were used primarily for detection of colorectal cancer and its precursors (adenomatous polyps). Disadvantages of these techniques were the lack of detailed information on both mural and extramural abnormalities and the resulting mediocre accuracy. Furthermore, the ionizing radiation exposure was a major drawback of these examinations especially as these often have to be repeated for treatment monitoring or screening of disease recurrence.

Ultrasound and computed tomography (CT) can be used for bowel assessment. They have high spatial resolution, give insight into mural and extramural abnormalities and are widely available. However, both have their limitations. Ultrasound has a limited field of view in areas where air or bone obscure viewing (e.g. pelvis), while reproducibility is a limitation. Primary drawback of CT is the ionizing radiation, while the contrast resolution is lower than for MRI.

MRI of the bowel was not possible when MRI was first introduced because long acquisition times in combination with respiratory movement and bowel peristalsis created large artefacts. In the last 10-15 years, fast imaging techniques that can be performed in a breath-hold were developed. Reduction of data-acquisition time, improved image quality and optimal resolution are developments in abdominal imaging that have led to the practicability of diagnostic assessment of the bowel with MRI. Currently, 1.5T MRI scanners are primarily used to evaluate the bowel, but in recent years 3T scanners have been used for MRI of the bowel. Because of the anticipated two-fold increase in signal-to-noise ratio compared to 1.5T, and therefore improvement in temporal or spatial resolution of the images, there is an increasing interest in adopting bowel MR protocols for 3T scanners.

Artefacts at 3T

Several different problems are associated with imaging at 3T. In general a direct transition from 1.5 to 3T is not possible. One needs to consider several aspects related to pulse sequence design, such as timings, radiofrequency pulses and specific absorption rate (SAR) issues when imaging at 3T.

Experience gained in for example imaging the brain at 3T does not necessarily apply to improve abdominal imaging. Many of the problems that are associated with imaging at 3T differ between regions. The main constraints in 3T imaging are related to changes in tissue T1 and T2 relaxation parameters, SAR limitations, susceptibility artefacts, B1-inhomogeneity artefacts and steady state free precession (SSFP) banding artefacts. A problem of the first generation 3T scanners for abdominal imaging is the reduced field of view in the z-direction, which is often limited to 30 cm. Current 3T MRI scanners have field of views that are comparable to 1.5T scanners.

In general one should be aware of the changes in T1 and T2 values when using 3T. T1-values are prolonged at 3T, whereas T2-values are slightly shortened. The change in T1 and T2 relaxation parameters at 3T imply the decrease of T1 contrast in T1-weighted images and the decrease in the SNR of T2-weighted images, if TE and TR parameters are used that are identical to the ones used at 1.5 T. Direct adoption of imaging parameters used at 1.5T without adjustments will therefore possibly alter the diagnostic quality of the images. Avoiding T1-weighting in spin echo sequences at 3T necessitates the use of higher TR-values which has as drawback an increased scan time.

Energy deposition in tissue due the RF transmission can be limited by keeping SAR levels below 4 W/kg over the whole body. However, the SAR increases by a factor 4 when going from 1.5 to 3T. Here again, direct transition of sequence parameters (e.g. flip angles) from 1.5T to 3T will not be possible. Sequences working close to SAR limits (e.g. turbo spin echo and SSFP sequences) are consequently limited at 3T. In fast spin echo sequences one might therefore consider to use refocusing angles much smaller than 180 degrees and to use parallel imaging factors much larger than 2, thus making use of the increased SNR at 3T.

Susceptibility artefacts are a well known source of MRI imaging artefacts. These artefacts arise in interfaces between different tissues in the body, e.g. bone and soft tissue. A local shortening of T2 can degrade the signal and in more severe cases significant distortion and even signal voids can occur. Those artefacts increase with field strength and consequently at 3T they are more pronounced. Fortunately, in fast imaging sequences with very short TEs susceptibility artefacts only play a minor role, although in echo planar imaging used for
diffusion weighted imaging the effects can be very detrimental. In the latter case one should use either small field of views in the phase encoding direction or high parallel imaging factors to keep the TE as short as possible. In addition the effectiveness of prepulses, e.g. for fat suppression, can also be decreased by B0 inhomogeneity that is present near tissue interfaces.

B1-artefacts are among the most problematic artefacts hampering clinical routine use of 3T abdominal imaging. Due to the high dielectric constant of tissue (water) the B1 wavelength is decreased from 234 cm in free space to approximately 30 cm in the body. The latter is of the order of magnitude of the FOV of many body imaging protocols and therefore artefacts resulting from the generation of standing waves within the field of view can occur. These artefacts consist of strong signal variations across the image. In areas of high signal intensity constructive interference occurs and areas of signal drop coincide with areas of destructive interference (figure 1). In addition conductivity effects also tend to increase B1 field inhomogeneity. In regions of highly conductive tissue such as ascites current can be induced by the rapidly changing RF field. The induced current tends to oppose the RF field therefore causing local signal drops in the image. Presently multi transmit systems are becoming available that largely reduce the effects of B1-homogeneity by use of sophisticated methods for B1-shimming. Several RF transmit coils can be combined whereby the phase and amplitude of the signal emitted by each coil are adjusted in order to obtain a homogeneous B1 field.

Fast 3D imaging sequences with very short TRs below 10 ms are frequently being used in abdominal imaging because of their imaging speed while still maintaining high SNR and spatial resolution. Pulse sequences falling under the classification of balanced (b-)SSFP sequences such as b-FFE (Balanced fast field echo), TrueFISP (Fast imaging with steady state precession) and FIESTA (Fast imaging employing steady state acquisition) are very attractive for discrimination between lumen and bowel wall. However, b-SSFP sequences suffer from banding artefacts that become more prominent with increasing field strength (figure 2). The bands in the image originate from the dephasing of the transversal magnetization in each TR due to magnetic field inhomogeneities. Furthermore, the combination of b-SSFP with fat suppression can be problematic in terms of SAR, since b-SSFP sequences require high flip angles (~45 degrees) to generate the typical contrast between lumen and wall. At present no straightforward solution for the banding artefact is available.

### Patient preparation

#### Oral contrast agents

Bowel pathology can only be accurately assessed when there is adequate luminal distension. Only large masses can be identified without distension. Collapsed bowel segments hamper adequate assessment of bowel wall pathology, as it can imitate or conceal wall related lesions. Small bowel distension can be achieved either by naso-duodenal intubation (MR enteroclysis) or oral contrast (MR enterography). Both have some drawbacks; enteroclysis is more burdensome and exposes the patient to radiation (during the naso-duodenal intubation under fluoroscopic guidance), whereas enterography is less accurate in showing proximal small bowel lesions. Therefore the authors recommend MR enteroclysis in all new patients and MR enterography for Crohn’s disease follow-up.

Distension of the large bowel can be obtained either by rectal insufflation of gas, administration of water-based enemas or oral contrast agents. Important features of a bowel contrast agent are a high contrast resolution between the bowel wall (and pathology) and the bowel lumen and homogeneous signal intensity of the lumen.

There are three types of contrast agents; positive (bright lumen), negative (dark lumen) and biphasic (bright on one sequence, dark on the other). Bright lumen contrast agents are contrast agents which are gadolinium-based. Gadolinium causes both T1 and T2 shortening. When applying ‘normal’ concentrations, the T1-shortening effect predominates causing high signal intensity on both T1 and T2-weighted images. However, when the gadolinium concentration is much higher, T2-shortening occurs as well, causing signal intensity loss in all sequences. Nevertheless, T2-weighted sequences are more sensitive for this effect, which causes dark appearing lumen on T2-weighted images (thus making this type of contrast biphasic). With the bright lumen technique, intraluminal lesions (polyps) can be seen as dark appearing filling defects.

When using negative contrast agents (the dark lumen approach), the lumen of the bowel appears hypointense on both T1 and T2-weighted images. This is caused by local field inhomogeneity induced by the contrast agent causing a signal drop on both T1 and T2-weighted images. When a paramagnetic contrast agent is given intravenously, this causes the bowel wall/lesion to enhance and thus improving the contrast between the bowel wall and lumen.
Biphasic contrast agents differ from bright and dark lumen agents because they appear bright on one sequence, usually T2, and dark on the other, usually T1. Biphasic contrast agents are most commonly applied in small bowel MR imaging. Water is the most easily available biphasic contrast agent, but as water is fast absorbed by the gut, an osmotic agent is often added to improve luminal distension.

For small bowel imaging, the authors prefer to use a biphasic contrast agent (mannitol, 2.5%, 1600 mL) as this results in optimal contrast between bowel wall and lumen at both T1-weighted and T2-weighted sequences. For MR enterography the patient starts to drink the contrast agent 1 hour before the exam, in aliquots of 1 cup per 5 minutes. When using mannitol, colonoscopy with electrocoagulation should be avoided after the MRI, because methane and hydrogen are formed when mannitol dissociates. As an alternative, the sugar alcohol sorbitol (2.5% in 1500 mL water) can be used. For MR enteroclysis, the contrast medium is infused through a naso-duodenal tube at 80-120 mL/min. During the infusion of the contrast, thick-slab SSFSE images are acquired to assess if the contrast has reached the colon. When this is the case, the MR exam can be performed.

Bowel preparation schemes for 1.5T can also be implemented at 3T. For the same contrast agent concentration, the change in T1 parameter is larger at 3T than at 1.5T, due to differences in resonant frequency of water and fat. This artefact has implications for MR colonography which uses water based enemas for bowel distension. In MR colonography the appearance of dark boundaries due to chemical shift artefacts at fat-water interfaces can hinder visualization of the bowel wall. To overcome these artefacts the bandwidth can be increased, although this reduces SNR. When using effective fat suppression techniques the consequences of this artefact will however be minor.

MR colonography is used for diagnostic evaluation of the large bowel and differs from routine abdominal imaging in the way that it uses colonic distension for optimal visualization of bowel lesions and secondly it uses either cleansing or faecal tagging for preparation of the bowel.

Water or a barium-containing mixture are generally used as bowel distension agents. Carbon dioxide (CO2) or room-air have been studied as gaseous distending agents in rectal insufflation for MR colonography and result in low signal intensity on T1- and T2-weighted sequences (figure 3). Although most studies report on room-air insufflation, CO2 has the advantage of less discomfort after the examination, due to faster re-absorption by the gastro-intestinal tract than room air. Studies on colonoscopy demonstrated better acceptance by patients of CO2 than room-air. Both automated and manual insufflation is used in gaseous distension, although automated insufflation benefits from monitoring and regulation of constant intra-colonic pressure as this might vary due to ileo-coecal reflux and gas incontinence. Up to now, diagnostic performance of MR colonography with gaseous distension varies. Susceptibility artefacts, due to field heterogeneities, are more prone at soft tissue-air interfaces and increase with the increase of the magnetic field strength. As colonic distension by air-based and water-based contrast agent is one of the prerequisites of MR colonography, the latter is prone for susceptibility artefacts at the interface of gas and bowel wall. The use of fast imaging 3D sequences with very short TEs (3-4ms) decreases susceptibility artefacts in MR colonography with CO2 distension. Consequently susceptibility artefacts at 3T are most pronounced in 2D gradient echo sequences with echo times in the range of 50-80 ms, therefore the use of 3D sequences is recommended.

Although gaseous distension is akin to CT-colonography, most studies until now concerned water-based enemas. Bowel distension with water-based enemas consisting of tap water or a mixture of water and gadolinium have been used. Generally a volume of 1 to 3 litres of water-based distension agent is used to maintain constant intracolonic distension. Signal intensity of water is high on T2-weighted images and low on T1-weighted sequences. When labelled with gadolinium, T1-weighted images appear high in signal (bright lumen) (figure 3).

Chemical shift artefacts are increased at high-field imaging due to the increased difference in resonant frequency of water and fat. This artefact has implications for MR colonography which uses water based enemas for bowel distension. In MR colonography the appearance of dark boundaries due to chemical shift artefacts at fat-water interfaces can hinder visualization of the bowel wall. To overcome these artefacts the bandwidth can be increased, although this reduces SNR. When using effective fat suppression techniques the consequences of this artefact will however be minor.

Faecal tagging

Faecal residue can mimic or obscure bowel pathology and therefore hamper adequate diagnostic assessment of the large bowel. To overcome this impediment, the colon can be cleansed by purgative solutions as in conventional colonoscopy. In general sodium phosphate solutions and polyethylene-glycol (PEG)-electrolyte solutions are used for cleansing. Faecal tagging as a bowel preparation method was introduced similar to its use in CT-colonography. Faecal tagging refers to consistently labeling stool by oral intake of a contrast agent equivalent to 1.5T less contrast has to be administered. In general one should be aware that when this is the case, the MR exam can be performed.
agent with a regular meal, in that way providing for sufficient contrast between the colonic wall and the colonic lumen with its faecal content. Furthermore, as bowel purgation was considered burdensome, faecal tagging was also introduced to avoid extensive cleansing of the colon.

Several faecal tagging strategies have been proposed in MR colonography research. Tagging agents containing high concentrations of barium sulphate were studied. Initial results were promising as differentiation of colonic wall and lumen was exceptional, yet subsequent research demonstrated less encouraging results regarding patient acceptance and image quality. Following these results, different solutions containing barium were studied concerning diagnostic accuracy and patient acceptance resulting in improved outcomes. Furthermore, gadolinium-based faecal tagging agents were studied, however in preliminary research high costs of the tagging agent hindered extensive application.

Diagnostic accuracy of bright lumen MR colonography is influenced by false positive findings caused by residual air and faeces. As most lesions are not affected by gravity as opposed to residual air and faeces, the examination is performed in both supine and prone position. In the dark lumen approach dual positioning is not required to avoid false-positive findings due to air/faeces residue as lesions of the bowel wall are enhanced; nevertheless dual positioning is in fact essential for optimal bowel distension. To avoid false-positive findings in dark lumen MR colonography, pre- and post contrast imaging is performed.

For MR colonography, the authors prefer to use the dark lumen approach using automated CO₂ insufflation for bowel distension as this improves adequate colonic distension and patient acceptance. As in CT-colonography, faecal tagging with an iodinated contrast agent is applied for adequately labelling the stool, causing high signal intensity of the stool at T1 and T2 weighted sequences. Furthermore, the laxative effect of the iodine provides for liquid stool with a good mixture of stool and contrast. To ensure sufficient colonic distension of all bowel segments, prior to data acquisition, the insufflation is performed while changing the patient’s position from its right lateral side to the left lateral side. The intracolonic pressure is monitored by an automated insufflator. To our knowledge, no MRI compatible insufflator exists; therefore long tubing is used for insufflation with the insufflator outside the MR suite.

### Sequences at 3T

When transferring bowel imaging MR sequence protocols from 1.5T to 3T modifications are mandatory because of differences in tissue T1 and T2 relaxation parameters (longer T1 and shorter T2 relaxation times at 3T) and SAR limitations (see specific sequence for details).

All sequences must be performed in 15-25 sec breath-holds. If the breath-hold is over 15 seconds hyperventilation directly prior to the sequence is recommended. Careful explanation of the procedure and length of the breath hold is mandatory (see table 1 for recommended scan parameters).

### Table 1: Recommended scan parameters for 3T MR imaging of the bowel

<table>
<thead>
<tr>
<th>Sequence:</th>
<th>SSFSE coronal</th>
<th>SSFSE axial</th>
<th>SSFSE axial With fat saturation</th>
<th>3D T1w gradient echo coronal</th>
<th>3D T1w gradient echo axial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition time (ms)</td>
<td>800</td>
<td>800</td>
<td>1450</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Echo time (ms)</td>
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<td>65</td>
<td>70</td>
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<td>1.0</td>
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<td>Flip angle (degrees)</td>
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<td>90</td>
<td>90</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
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<td>4</td>
<td>7</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of signal averages</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fat saturation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>Matrix</td>
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<td>256°200</td>
<td>288°233</td>
<td>200°200</td>
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<tr>
<td>Field of view</td>
<td>400°400</td>
<td>375°300</td>
<td>375°300</td>
<td>400°400</td>
<td>375°300</td>
</tr>
</tbody>
</table>
Single-shot fast spin echo (SSFSE)
This sequence is recommended as initial sequence as it gives an overview of the abdomen. Both coronal and axial sequences must be performed. Since one slice is acquired per shot, this sequence is relatively insensitive to motion artefacts although intraluminal flow artefacts can occur. The normal bowel wall has uniform low signal intensity on this sequence; wall oedema (e.g. in active inflammation) and mural fat (e.g. in patients with longstanding inflammatory bowel disease) have high signal intensity. To differentiate between oedema and intestinal fat, a fat-suppressed sequence is recommended.

Theoretically, 3T MRI scanners have twice the SNR compared with a 1.5T scanner. One study has assessed that for SSFSE the ultimate gain in SNR is only 1.74. This is due to specific problems at 3T, such as SAR limitations. In comparison to 1.5T, the TE of this sequence needs to be shortened. The 180º-refocusing pulses need to be reduced because of SAR limitations, which lowers the SNR. When shortening the TE, the SNR improves but this causes some loss in T2 contrast. In addition, standing wave artefacts can be present in patients with ascites.

Three-dimensional T1-weighted gradient echo
The overall enhancement and the enhancement pattern of the bowel wall after intravenous contrast injection is best assessed on this sequence. The authors recommend administering intravenous Gadolinium (0.1 ml/kg) and start the scan after 60 seconds. This is specifically important in patients with inflammatory bowel disease where enhancement is one of the features used for determining disease activity. The sequences should be performed in coronal and axial plane if isotropic voxel sizes are not available. Also, the use of fat saturation is recommended to optimize the contrast between enhancing bowel wall and mesenteric fat. Because this sequence is very sensitive to (peristaltic) motion, it is advised to give an anti-peristaltic drug, such as N-butyl scopolamine bromide or glucagon. In the USA N-butyl scopolamine bromide is not FDA approved for this application and can not be used.

3D Spoiled gradient-echo sequences (e.g. THRIVE, VIBE or FAME) are robust sequences that can be implemented without much adaptation on 3T, with a good SNR and contrast-to-noise ratio.

Balanced steady-state free precession (b-SSFP)
B-SSFP sequences combine their contrast from both T1 and T2 in a ratio (T2/T1). This sequence is often used at 1.5 Tesla for assessment of the small bowel wall as it provides a high contrast anatomical overview. Thereby, this breath-hold sequence is not sensitive to motion. At 3T, banding artefacts (appearing as bright and dark stripes in the image) and low SNR substantially degrade the usefulness of this sequence. When increasing B0-homogeneity the banding pattern migrates to the borders of the field of view. However this solution is not very practical at 3T, since the effectiveness of shimming is limited at 3T. Another solution is to vary the location of the banding pattern in consecutive acquisitions6, as illustrated in figure 2. This can give good results, but the imaging time is increased and the final image is prone to blurring due to differing breath hold positions. A satisfactory solution to reduce the banding artefact has not been proposed so far.

Diffusion-weighted imaging (DWI)
DWI reflects the changes in water mobility caused by interactions with macromolecules and cell membranes. This can be measured by the apparent diffusion coefficient (ADC value). DWI at 3T can benefit from increased SNR, but also image quality can suffer because of increased magnetic susceptibility. These artefacts can be limited using parallel imaging techniques, thus shortening imaging time and TE.

At 1.5T for detection of active Crohn’s disease, DWI showed decreased ADC values in patients with active disease with a sensitivity of 95% and a specificity of 82%7. To our knowledge, no study has been performed at 3T.

Developments in DWI demonstrated valuable potential in the field of oncology for detection of cancer and response prediction to therapy. However, to our knowledge, all studies in DWI of the bowel have been performed at 1.5T or lower field strength MR imaging.

Cine Imaging
To obtain information about small bowel motion and peristalsis, it can be useful to add a cine MRI sequence. Especially adhesions can be visualized by fixation of bowel loops and lack of normal peristalsis. On 1.5T, this is usually done with the b-SSFPE sequence. On 3T, SSFSE can be used instead, acquiring 2 slices per second.

Imaging Indications

Inflammatory bowel disease
Crohn’s disease and ulcerative colitis are the two main diseases that comprise IBD. IBD is characterized by disease remissions and exacerbations. Crohn’s disease can be present in the
whole gastrointestinal tract, but is most commonly located in the terminal ileum. Colonic involvement is also often present. Specific for Crohn’s disease is the presence of skip lesions where pathologic bowel wall lesions are separated from normal bowel wall. Crohn’s disease is a transmural disease, so all bowel wall layers can be involved and extra intestinal manifestations (fistulas, abscesses) can occur.

Ulcerative colitis is a mucosal inflammatory disease and is confined to the colon and rectum with a predilection for the distal colon and rectum, though ‘backwash ileitis’ can mimic terminal ileitis. Because the inflammation occurs only in the mucosal layer of the large bowel, extra-enteric manifestations are very rare.

Diagnosis or follow-up (therapy monitoring) for Crohn’s disease is the most important indication for MR imaging of the small bowel. MRI is capable of diagnosing Crohn’s disease and monitoring therapy response. In a meta-analysis sensitivity was 93.0% and specificity was 92.8% for detection of Crohn’s disease. All studies in this meta-analysis were performed at 1.5T or less. Only one study has been performed that focused on evaluating Crohn’s disease activity at 3.0 Tesla. This study demonstrated the feasibility of 3T MR enterography in a small cohort of twenty Crohn’s disease patients. Two MR parameters were assessed; correlations were found between the CDEIS and bowel wall thickness and enhancement. As of yet, to our knowledge no studies have been performed that compared 1.5T with 3T for the accuracy of diagnosing Crohn’s disease.

A recent meta-analysis determined the accuracy of MRI in grading disease activity. Seven studies were included (one at 3T), of which six examined both the small and the large bowel. MRI correctly graded 91% of frank disease and 62% of patients in remission or with mild disease. This low accuracy in grading of mild disease activity (presented often as small mucosal ulcerations) might be due to low spatial resolution in MRI or the inability of MRI to detect small lesions.

The role of MR colonography in Crohn’s disease patients is limited. It has been studied in a few studies and only at 1.5T. Sensitivity for segment-based inflammation was 32% and specificity was 88%. Rimola and colleagues have published an educational exhibit about 50 IBD patients in whom they performed MR colonography, but did not report statistical evidence.

The place of MR imaging in ulcerative colitis patients is limited to MR colonography, as ulcerative colitis is limited to the colon. Only the mucosa is affected and especially in mild disease, where there is only mucosal oedema and hyperaemia, spatial resolution is to low to detect this. When there is severe disease, the colonic wall changes can show ulcerations, wall thickening and enhancement but less than in Crohn’s disease because the inflammation is not transmural.

In Crohn’s disease patients, current guidelines from the European Crohn’s and Colitis Organisation (ECCO) recommend performing ileocolonoscopy for initial diagnosis and to assess the extent of the disease, either by small bowel MRI or CT. They add that because of the radiation risk in young patients, MR should be considered where possible. The American College of Radiology recommends performing an abdominal CT, though they indicate that MRI may have the same sensitivity and specificity. The choice of examination therefore depends on institutional resources and preferences. For ulcerative colitis, ECCO guidelines do not recommend MR imaging as routine imaging technique.

Imaging features for IBD
Several imaging features are known to reflect active Crohn’s disease activity.

Bowel wall thickening is used as one of the most important parameters to assess disease activity since a long time. Traditionally, this is best assessed on b-SSFP images, but if these are not available, SSFSE can also be used for this purpose (figure 8). There is no consensus in the literature on the exact upper limit of normal bowel wall, however often a bowel wall > 3 mm is considered as thickened. The thickening can be due either to fibrosis or oedema of the bowel wall. In a previous study on a 3.0 Tesla scanner, a significant correlation was found for bowel wall thickness and the CDEIS. False-positive findings mimicking thickened bowel wall can occur when the bowel is not optimal distended; therefore all sequences have to be scrutinized for the images with the most optimal distension. This primarily concerns MR enterography; bowel loop distension is optimized at MR enteroclysis.

Enhancement of the bowel wall. One of the most important findings for disease activity is the enhancement of the bowel wall of intravenous contrast injection. In a meta-analysis, enhancement was one of the most important parameters for Crohn’s disease activity. To our knowledge, only one study assessed enhancement of bowel wall at 3T. In that study, a significant correlation was found between CDEIS and mural enhancement (figure 8).
T1-stratification (layered appearance of bowel wall) can be seen when the bowel wall enhances after intravenous contrast injection. Enhancement can be mucosal (innermost layer of bowel enhancing), homogeneous (all bowel wall enhancing equally) and layered (both mucosal and serosal bowel wall layers enhancing with a central band of relatively reduced enhancement). At 1.5T a multilayered appearance of the bowel wall was associated with inflammatory activity measured at histology\textsuperscript{13} (figure 9).

High T2 signal intensity of the bowel wall is most often present when there is inflammation/oedema of the bowel wall, such as in active Crohn’s disease. Fat suppression is recommended to distinguish oedema from fat. At 1.5T, the signal intensity of the bowel wall compared to the signal intensity of cerebrospinal fluid was positively correlated with disease activity measured at histology\textsuperscript{13} (figure 9).

Stenosis. A stenosis can be defined as a luminal narrowing of the bowel wall of more than 50%. This can be evaluated on all sequences. If a pre-stenotic dilatation is present, this indicates (partial) obstruction. A stenosis can be either caused by fibrosis or inflammation. If the stenosis is due to inflammatory activity, medical therapeutic options should be considered. Therefore it is important to differentiate between fibrosis and inflammation. After intravenous contrast, active Crohn’s disease does enhance whereas a fibrotic stenosis does not enhance.

Verification of the degree of obstruction on the different sequences performed during the MR enterography procedure gives important information on the degree of obstruction. The sensitivity of detecting a stenosis with MR enterography at 1.5T is 86% versus 100% for MR enteroclysis\textsuperscript{14}. The higher accuracy with MR enteroclysis is due to the better distension, but in daily practice enteroclysis can also be performed because the obstructed flow due to the stenosis gives rise to a pre-stenotic dilatation. Also cine imaging can be performed to assess the motility of the bowel wall (see sequences).

The presence of the comb sign indicates increased blood flow in the vasa recta of a bowel segment. The mesenteric vessels are arranged like the teeth of a comb, hence the name comb sign. This can be seen on b-SSFP images or on T1-weighted images. It is considered to indicate the presence of active disease (figure 8).

Creeping fat or fibro fatty proliferation is the stranding and retracting of mesenteric fat around affected bowel segments. Most often, this phenomenon can be seen in patients with a past episode of active inflammatory bowel disease. The presence of creeping fat can best be assessed on SSFSE images.

Traditionally, the presence of ulcerations can best be assessed on b-SSFP images, but also on SSFSE. Deep linear ulcers appear as thin lines of high signal intensity longitudinally or transversely (fissure ulcers) orientated within the thickened bowel wall (figure 10). On T1-weighted images, ulcerations can be seen as a focal defect in the enhancing bowel wall.

Lymph nodes. Patients with Crohn’s disease often have enlarged mesenteric lymph nodes (> 1 cm). These can best be visualized on b-SSFP sequences. At 3T, these can best be seen on a T1-weighted sequence (figure 11). Lymph nodes may enhance, although the relevance of this finding for determining disease activity is disputed.

Fistula and abscess. Fistulas and abscesses are extraluminal manifestations of Crohn’s disease that can best be seen on post-contrast T1-weighted images, because of their enhancement after intravenous contrast due to inflammation (figure 12). A non active fibrotic track will not enhance. In abscesses, the centre will have a hypointense signal intensity because of the fluid content, whereas the wall of the abscess enhances.

Detection of colorectal polyps and colorectal cancer

Colorectal cancer (CRC) is the second leading cause of cancer related death in most western societies. Colorectal adenomas are considered to be the benign precursors in the majority of cases of colorectal cancer. Efforts have been made to reduce mortality and incidence by screening and surveillance. Colonography with computer tomography (CT-colonography) has gained clinical acceptance as it is less invasive and burdensome compared to conventional colonoscopy and has proven its role as alternative to colonoscopy in symptomatic patients. Importantly, it has also been demonstrated to have good accuracy for screening\textsuperscript{15}. Drawback of CT-colonography is ionizing radiation exposure which could be prevented by using MR colonography. MR colonography has been studied over the last decade for detection of colorectal cancer and the precursor of colorectal cancer, colorectal adenomas\textsuperscript{16}. 
Large colorectal lesions are highly suspicious for colorectal cancer at MR colonography, especially obstructing masses. For polypoid lesions malignancy cannot be determined at MR colonography. However, the risk of colorectal cancer within an adenoma is size-related and therefore polyps are categorized in three categories: large polyps of 10 mm and larger, intermediate polyps of 6-9 mm and small polyps of 5 mm and smaller. In large polyps a prevalence of advanced histology was demonstrated to be 30.6% and malignancy in approximately 10%. The prevalence of advanced histology in polyps intermediate sized (6-9 mm) was 6.6% with a range of 4.6-11.7% while the chance of malignancy is smaller than 1%. For polyps of ≤ 5 mm advanced neoplasia was demonstrated to be present in 1.7% (range 1.2-2.0%) and the risk of malignancy was demonstrated to be very small (0.06%). In CT-colonography there is consensus that patients are referred for colonoscopy when polyps of 6 mm and larger are demonstrated.

Primarily research has focused on dark lumen MR colonography with the use of bowel cleansing and a water-based enema; the results were encouraging as no false-negative findings were demonstrated. Initial research using the bright lumen method for MR colonography demonstrated high diagnostic accuracy for large lesion detection, though diagnostic performance for smaller lesions varied. Most research was performed at 1.5T or less. The majority of studies have been performed in patients with symptoms of colorectal cancer or patients under surveillance. A systematic review on diagnostic accuracy of detection of (precursors of) colorectal cancer with MR colonography showed encouraging results. Thirteen studies, both bright and dark lumen MR colonography studies, were evaluated. Furthermore, two study groups performed MR colonography at 3T MR scanners, however one study was executed on both 1.5T and 3T MR systems. In this study, unfortunately, differences in diagnostic accuracy, image quality and patient acceptance were not mentioned. The systematic review on colorectal cancer detection with MR colonography showed excellent results as sensitivity was 100%. For the detection of large polyps (10 mm or larger) the per-patient sensitivity was 88% (95% CI 63–97%) and specificity 99% (95% CI 95–100%) and the per-polyp sensitivity was 84% (95% CI: 66-94%). No conclusions could be drawn for polyps of intermediate size and smaller than 6 mm, due to heterogeneous data.

Although this systematic review demonstrates promising results, it has to be taken into account that data on diagnostic accuracy of MR colonography in detection of colorectal cancer and colorectal polyps is heterogeneous and to date, no consensus has been reached on patient preparation method and technique.

The results of MR colonography in symptomatic patients can not be extrapolated to screening. One prospective study, performed on a 1.5T MR system, has focused on asymptomatic patients with a normal risk profile for colorectal cancer. The prevalence for polyps of 10 mm and larger was demonstrated to be 6.3%. Although the overall patient based sensitivity and specificity was 36.4% and 90.2%, for intermediate sized lesions and lesions of 10 mm and larger, sensitivity was 60% and 70% respectively and 100% specificity was demonstrated.

Other indications
As of yet, only few studies have been performed that assessed the accuracy of 3T MRI Crohn’s disease or colorectal polyp and colorectal cancer detection. For other indications for small or large bowel MRI discussed here, there is no data on the use of 3T.

As MRI permits superior soft tissue resolution, MRI is able to detect complications of diverticular disease like abscesses, fistulas and free abdominal fluid. To date, MR colonography has shown promising results in evaluation of acute diverticulitis; sensitivity was 86%, specificity 92% for detecting diverticular disease with the dark lumen method at 1.5T. The role of 3T MRI is not yet established.

MR imaging for acute abdominal pain, specifically appendicitis, was not often used because of long scan times and logistical problems. As faster sequences were developed, more interest has developed for MRI for this indication. Most studies have been performed on 1.5T or less and many concern pregnant patients. A systematic review has shown that sensitivity of MRI for diagnosing appendicitis is 80% and specificity is 99% as of yet no data exists on 3T MRI for appendicitis.

Peutz-Jeghers syndrome is characterized by the occurrence of hamartomatous small and large polyps and these patients require frequent monitoring because these polyps can degenerate to a malignancy and therefore need to be resected. No studies have been performed to test the accuracy for polyp detection at 3T MRI. For 1.5T, polyps < 5 mm are not detected because of low spatial resolution.

Celiac disease is a gluten-sensitive enteropathy of the small bowel. Because of the lack of specific symptoms, diagnosis can be difficult. Patients whom are referred for small bowel

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MR for non-specific gastrointestinal complaints can have celiac disease as their underlying pathology. The most specific sign for celiac disease on MR are fold pattern abnormalities. Ileal jejunisation denotes an increase in ileal folds, whereas the folds in the jejunum decrease or completely flatten.

Small bowel malignancies are relatively uncommon. Carcinoid is the most common primary small bowel tumour. At 1.5T carcinoid either presents as a concrete mass that enhanced after intravenous contrast or as a uniform bowel wall thickening which showed also enhancement. Small bowel lymphomas are usually of the non-Hodgkin type. They are mostly located within the bowel wall and enhance after intravenous contrast is given.

1.5T versus 3T
Theoretically, 3T MRI scanners have twice the SNR compared with a 1.5T scanner. However, due to specific problems (such as SAR) the ultimate gain in SNR is often less, e.g. 1.7 for SSFSE sequences. The gain in SNR at 3T is used in other fields such as neurovascular imaging to obtain a better imaging quality. In these fields 3T has become superior to 1.5T imaging.

For bowel imaging however, imaging at 1.5T is still the standard in most hospitals. In Crohn’s disease patients, abdominal MR imaging at 3T is feasible but future research will have to point out if diagnostic accuracy rates are actually higher than at 1.5T.

To our knowledge, the only comparative studies of 3T versus 1.5T for bowel diseases reporting data concern the detection of colorectal polyps and cancer. Wessling et al. demonstrated no significant difference in detection of polyps larger than 6 mm in a phantom (10 sessile polyps: 4x2mm, 3x3mm, 1x4mm, 1x6mm, 1x8mm). This study demonstrated overall sensitivity for polyp detection of 56% at 1.5T and 55% at 3T.

Moreover, a study in 40 patients carried out by Rottgen and co-workers demonstrated no overall significant difference in image quality at 3T compared to 1.5T. 2D b-SSFP images were found to be superior at 1.5T, but there were no significant differences in 3D T1-weighted fat-suppressed gradient echo and SSFSE. Furthermore, a phantom model with polypoid lesions was studied both at 1.5T and 3T. The study demonstrated significantly better visualization of the polyps at 1.5T and visualization of artificial polyps. However Saar et al. demonstrated a sensitivity of 100% for colorectal lesions larger than 6 mm as all carcinomas (4/4) and polyps (16/16) were identified at 3T using two different T1 weighted 3D gradient recalled echo sequences. Diagnostic quality was reported to be excellent in 94% and 92% respectively for the two sequences.

It can be expected that in the future the advantage of 3T MRI will be further exploited in techniques such as very fast dynamic contrast-enhanced sequences. In Crohn’s disease, it is known that bowel wall enhancement is a marker of disease activity. DCE-MRI is a technique that acquires images during the delivery of contrast in the tissue of interest (in this case the bowel), thus highlighting the dynamic response of the tissue to the inflow of blood and the subsequent distribution in the extracellular fluid space. Analysis of the time-dependent changes of signal intensity on dynamic contrast-enhanced MR images might provide valuable information about disease activity in Crohn’s disease patients.

Conclusion
The use of abdominal protocols for 3T has increased over the last few years. Although it is feasible to perform MR of the small bowel and MR colonography at 3T, further research has to be performed to determine whether 3T performs better than 1.5T. At this moment, there is no compelling evidence that favours the use of 3T MRI over 1.5T MRI for imaging bowel diseases. Technological advances like B1-shimming and increased B0 homogeneity in the z-direction of modern 3T scanners, will contribute largely to the clinical acceptance of 3T MRI scanners for abdominal imaging.
Reference List


