Virtual Colonoscopy by MRI: State-of-the-Art and Future Directions

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Colorectal cancer screening

Colorectal cancer remains the second most common malignant cancer in the industrialized world associated with considerable morbidity and mortality. More than 130,000 newly diagnosed patients and 50,000 deaths are attributed to colorectal cancer each year in the United States [1]. Nearly 6% of the population will develop colorectal cancer during their lifetime [2]. Most colon cancers develop from nonmalignant colonic adenomas or polyps. Reflecting this adenomatous pathogenesis of most colorectal cancers [3,4], polyp screening with subsequent polypectomy has been shown to constitute an effective approach for decreasing the incidence of this malignant tumor [5]. Cancer screening programs are suitable to reduce the cancer mortality by more than 80%. Colorectal screening for polyps can be regarded as one of the most promising preventive measures in medicine [6].

Most available colorectal screening modalities, including testing for occult fecal blood or double-contrast barium enema, are associated with insufficient diagnostic accuracy or poor patient acceptance [7,8]. Although optical colonoscopy has been established as an accurate method for the assessment of the colon, a large discrepancy between the screening potential and clinical reality remains apparent. This discrepancy is caused mainly by poor patient acceptance, which reflects considerable procedural pain coupled with the rigors of preparatory bowel cleansing and limits the acceptance of colonoscopy for colorectal cancer.

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screening [9,10]. Even in countries with free access to this diagnostic measure, participation in cancer screening programs based on optical endoscopy is suboptimal. This fact has motivated the development and evaluation of alternative modalities to assess the large bowel, including virtual colonography.

Virtual colonography is based on the acquisition of three-dimensional data sets based either on CT or MRI. These types of cross-sectional images offer considerable advantages over optical colonoscopy, the most significant of which relates the noninvasive character to the lack of procedural pain and discomfort. Virtual colonoscopy also is not limited to endoscopic viewing. The CT or MRI data sets can be evaluated in a multiplanar reformation mode on a postprocessing workstation, which enables the display of the colon from any desired angle. This type of multiplanar reformation analysis depicts the colonic wall, the colonic lumen, and all the surrounding abdominal morphology. Lesions can be located more accurately [11]. The entire colon always can be visualized even in the presence of stenotic tumors or elongated bowel segments. Visualization is often not possible in conventional colonoscopy, which is incomplete in up to 26% of the procedures [12–14]. Another characteristic of virtual colonography is the possibility of simultaneously assessing all other abdominal organs within the displayed field of view. Especially in patients with suspected colorectal tumors, the simultaneous assessment of the liver can be helpful for approving or excluding presence of liver metastases.

Recent studies have shown virtual colonography to be effective regarding the detection of relevant polyps that exceed 7 mm in size [15–24]. Neither CT nor MR colonography requires the administration of sedatives or analgetics, however, which are often used for conventional endoscopic procedures [15]. Both cross-sectional techniques are less painful than optical colonoscopy. Despite promising results, the impact of CT colonography as a screening method is uncertain, and patients are exposed to considerable doses of ionizing radiation. The radiation issue may even evolve into a public health concern, because screening examinations of the large bowel should be repeated at regular intervals (every 3–5 years) [25]. It seems favorable to focus on MRI for colorectal screening. MR colonography is not associated with any radiation exposure or other major side effects. Intravenous MR contrast agents are characterized by a more favorable safety profile than CT contrast agents because they lack any nephrotoxicity and are associated with far fewer anaphylactoid reactions [26,27].

**MR colonography: technical considerations**

Before the MR examination, bowel preparation must be performed in a manner similar to that required for conventional colonoscopy. MR colonography should be performed in the morning to avoid unnecessary patient discomfort. In contrast to optical colonoscopy, the administration of sedatives or analgesics is not required. Before the examination, patients should be screened for general contraindications to MRI, such as presence of metallic implants or severe claus-
trophobia. Hip prostheses, which are generally not considered a contraindication to MRI, may lead to strong artifacts in the region of the rectum and sigmoid colon and impede a sufficiently diagnostic image quality. Patients with hip prostheses should not be examined.

Similar to contrast-enhanced three-dimensional MR angiography, MR colonography is based on the principles of ultrafast imaging [15]. The use of an appropriate hardware system is mandatory. Because data acquisition must be performed under breath-holding conditions, the use of 1.5 T scanners equipped with strong gradient systems is mandatory. Whether MR colonography is possible depends mainly on the minimum repetition time. If it exceeds 5 msec, acquisition time of a three-dimensional data set that contains the entire large bowel will exceed 30 seconds, which is too long for comfortable breath holding. A sufficient distension of the large bowel loops must be accomplished. In their physiologic state, most bowel segments are collapsed and cannot be depicted properly. Bowel distension must be achieved by administering distending media (e.g., water solutions via a rectal catheter). Eventually, a high contrast between the bowel wall and the bowel lumen is important. Contrast mechanisms that allow the accurate display of the colonic wall depend strongly on the MR sequences applied and the use of intravenous and rectal contrast agents.

A combination of two large flex surface coils should be used for signal reception to ensure the coverage of the entire large bowel (Fig. 1). Before the rectal

Fig. 1. Clinical setup for MR colonography. The patient is placed in prone position on the examination table. For signal reception, a combination of two surface array coils is used. To provide sufficient bowel distension, the colon is filled with water using hydrostatic pressure.
enema, spasmolytic agents (eg, 20 mg of scopolamine or 1 mg of glucagon) should be administered intravenously, which helps to obviate bowel spasms and minimize artifacts caused by bowel motion. The use of spasmolytic agents leads to better bowel distension. The patient is placed in prone position on the scanner table. After the placement of a rectal tube, the colon is filled with approximately 2000 to 2500 mL of warm tap water using hydrostatic pressure (see Fig. 1). The filling procedure should be stopped either after the application of the entire amount of water or whenever a patient complains about inconveniences. Other authors propose the acquisition of monitoring sequences during the filling process (eg, non–slice select sequences that provide an update image every 2–3 seconds).

A combination of different sequence types that provide different contrast mechanisms can be acquired. After the collection of a localizer sequence, we propose the acquisition of two- or three-dimensional fast imaging with steady state precession sequences. Different vendor-specific names for these sequences have been introduced: TrueFISP (Siemens Medical Solutions, Erlangen, Germany), Balanced Fast Field Echo (Philips Medical Systems, Best, The Netherlands), and FIESTA (General Electric Medical Systems, Milwaukee, Wisconsin). Image features are characterized by a mixture of T1 and T2 contrast, which leads to a homogenous bright signal of the colonic lumen filled with water. The colonic wall and lesions that arise from it impress as dark filling defects (Fig. 2). In a second step, T1-weighted MRI should be performed in conjunction with the intravenous administration of gadolinium. After a first precontrast T1-weighted, three-dimensional gradient echo data set, paramagnetic contrast should be administered intravenously at a dosage of 0.2 mmol/kg. A rapid injection of normal saline should follow the paramagnetic contrast application. After a delay of 70 to 80 sec, the three-dimensional acquisition should be repeated (Fig. 3). Because of the stable contrast enhancement of the colonic wall over a relatively long time period, the acquisition of a T1-weighted three-dimensional gradient echo

Fig. 2. By means of TrueFISP imaging, the dark colonic wall can be distinguished easily from the bright colonic lumen.
sequence can be repeated. This repetition is mainly important in case of insufficient image quality (eg, because of patient movement or technical problems). Data collection is done in coronal plane for the fast imaging with steady-state precession sequences and the three-dimensional T1-weighted sequences. Finally, a T1-weighted two-dimensional fast low-angle shot (FLASH) sequence in axial plane is acquired, which allows the assessment of the adjacent abdominal organs in high image quality. All sequence parameters are listed in Table 1. After data acquisition, the enema bag is placed on the floor for draining the water, and the patient is removed from the scanner.

Data interpretation

After finishing the MR examination, all three-dimensional data sets should be transferred to a postprocessing workstation. At first, the contrast-enhanced three-

Table 1
Main sequences applied for

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<tr>
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<th>TrueFISP three-dimensional</th>
<th>T1-weighted FLASH three-dimensional</th>
<th>T1-weighted FLASH two-dimensional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition plane</td>
<td>Coronal</td>
<td>Coronal</td>
<td>Axial</td>
</tr>
<tr>
<td>Acquisition time</td>
<td>22 sec</td>
<td>21 sec</td>
<td>19 sec (^{a})</td>
</tr>
<tr>
<td>Repetition time (TR)</td>
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<td>3.1 msec</td>
<td>158 msec</td>
</tr>
<tr>
<td>Echo time (TE)</td>
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<td>1.1 msec</td>
<td>1.8 msec</td>
</tr>
<tr>
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<td>12°</td>
<td>70°</td>
</tr>
<tr>
<td>Slice thickness</td>
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<td>5 mm</td>
</tr>
<tr>
<td>Number of slices</td>
<td>96</td>
<td>120</td>
<td>70</td>
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\(^{a}\) Five acquisition blocks of 19 sec each.
dimensional T1-weighted images should be interpreted in the multiplanar reformation mode. This modality allows the radiologist to scroll through the data set in all three orthogonal planes. Whenever a colorectal lesion is suspected, the identical part of the large bowel is to be analyzed on the corresponding native scan. By measuring signal intensities of the lesions in native and postcontrast scan, a contrast enhancement value can be calculated. A secure differentiation between residual stool particles and real colorectal masses is possible. Colorectal lesions always strongly enhance (Figs. 4, 5), whereas residual stool never shows any contrast enhancement (Fig. 6). In a second step, the fast imaging with steady-state precession sequences should be analyzed. Because of the motion insensitivity, these images might provide additional information, especially in patients

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**Fig. 4.** Contrast-enhanced T1-weighted image displays a colorectal carcinoma in the descending colon with high signal intensity (arrow).

**Fig. 5.** T1-weighted imaging before (A) and after (B) intravenous gadolinium administration. A polyp that shows an avid contrast enhancement can be depicted in the sigmoid colon (arrow).
who are not able to hold their breath properly. Image quality of fast imaging with steady-state precession data may be superior because of the high contrast. These images do not provide any information about perfusion of the bowel, however. It may be difficult to distinguish between polyps and residual feces.

A special software tool can be used to enable the perception of the MR source data and virtual endoscopic views of the colon. MR data also should be assessed based on virtual endoscopic renderings. A virtual endoscopic fly-through improves depiction, especially of small lesions. The three-dimensional depth perception also allows the evaluation of haustral fold morphology, which enhances the observer’s ability to distinguish haustral from colorectal masses. The virtual fly-through should be performed in an antegrade and retrograde direction, which may help to visualize both sides of haustral folds and reduce the risk of missing relevant lesions.

**Diagnostic accuracy of MR colonography**

The impact of MR colonography for the detection of colorectal lesions has been evaluated in several studies. In a recent trial, MR colonography was compared with optical endoscopy, which served as the standard of reference [19]. One hundred patients with different clinical indications were examined prospectively. MR colonography was followed by subsequent optical colonoscopy on the same day. All patients underwent a standard bowel cleansing

Fig. 6. Comparison of non-contrast (A) and contrast-enhanced T1-weighted images (B) allows a reliable differentiation between colorectal masses and residual stool. As shown in this example, fecal material does not show a contrast enhancement and is already bright on the native T1-weighted scan (arrow).
protocol for MRI and colonoscopy. MRI was based mainly on the acquisition of pre- and postgadolinium T1-weighted data. Regarding data analysis, endoscopic and histologic results were compared with MR colonography. In six patients, optical endoscopy was incomplete, and two patients abandoned MR colonography because of claustrophobia. In 49 patients, 107 colorectal masses were depicted by means of endoscopy. The sensitivity rate of MR colonography for adenomas in a per-polyp analysis was 100% for polyps larger than 10 mm and 84.2% for polyps between 6 and 9 mm in diameter. When using a per-patient analysis, overall sensitivity rate for the detection of colorectal masses was 90%. There were a few false-positive results, and specificity of MR colonography amounted to 96%. MR colonography showed a high accuracy for the detection of adenomas and carcinomas larger than 5 mm.

The outlined results were confirmed by other trials. Ajaj and colleagues [17] evaluated the impact of MR colonography for the detection of colorectal polyps in a high-risk population. One hundred twenty-two subjects with suspected colorectal diseases underwent MRI and subsequent conventional endoscopy. None of the lesions smaller than 5 mm could be detected by MR colonography. As for the lesions between 5 and 10 mm, MR colonography correctly detected 16 of 18 lesions. All polyps larger than 10 mm and 9 carcinomas were correctly diagnosed on MR colonography images.

One major issue relates to the inability of MR colonography to detect colorectal masses smaller than 5 mm. The significance of this limitation is equivocal because these small lesions are not prone to malignant degeneration [28]. Further observational data on growth rates indicate that small polyps remain stable over a time range of 3 to 5 years. Small colorectal lesions probably will become detectable by MR colonography in the future. New technical refinements, including parallel acquisition techniques, will be implemented [29,30], and spatial resolution may be increased. Flat adenomas are likely to remain elusive, however.

In another study, the diagnostic accuracy of three-dimensional fast imaging with steady-state precession sequences was compared with contrast-enhanced T1-weighted data [31]. MR colonography was performed as described before in 37 patients with suspected colorectal lesions. The detection rate of colorectal masses and inflammatory lesions was separately assessed for T1-weighted data and fast imaging with steady-state precession sequences. Image quality also was analyzed. All patients underwent conventional colonoscopy as the standard of reference. Sensitivity of the T1-weighted MR colonography amounted to 78.9%. There were no false-positive results; residual stool could be distinguished from colorectal masses. By means of the fast imaging with steady-state precession sequences, however, two additional polyps could not be detected. The sensitivity rate only amounted to 68.4%. Because of the inability to distinguish residual stool particles from real colorectal masses, false-positive results were reported in 5 patients. Image quality was significantly superior to that of T1-weighted imaging, however, because of fewer motion artifacts. Fast imaging with steady-state precession sequences should be considered a complementary imaging modality, but the main diagnostic evaluation should be based on the T1-weighted data.
In contrast to optical colonoscopy, virtual colonoscopic studies are not limited to endoscopic viewing. Simultaneous information is collected for all surrounding abdominal structures, which may be of major interest in patients with colorectal tumor, because the liver also can be screened. The combination of pre- and postcontrast T1-weighted data and TrueFISP sequences with some T2-weighted characteristics can identify and characterize hepatic lesions reliably, including metastases, hepatocellular carcinoma, and hemangiomas. Further relevant lesions also can be detected, including other malignant tumors (eg, prostate cancer or bone metastases) [17].

**Indications of MR colonography**

There are several proven indications for MR colonography. In patients with incomplete endoscopy caused by stenoses or elongated bowel segments, virtual endoscopy (either based on MRI or CT) has been shown to provide useful additional information [32–34]. Virtual colonography is associated with significantly higher completion rates. Bowel elongation does not harm the visualization of colonic segments at all. Only a high-grade stenosis prohibits the passage of water required for distending prestenotic segments (Fig. 7).

A recent trial evaluated the impact of MR colonography in patients who had undergone incomplete endoscopy [32]. Presence of colorectal pathologic conditions was assessed on a segmental basis in 37 patients. Although optical colonoscopy could not reach almost 50% of the potentially visible colonic segments, only 4% of the bowel segments were not assessable by means of MRI.

Fig. 7. Patient with a large stenosis of the transverse colon after radiotherapy (arrows). In contrast to optical colonoscopy, MR colonography allows the depiction of the prestenotic colonic segments. Note the good distension of the ascending colon despite the high-grade stenosis, which is displayed on the T1-weighted scan (A) and the TrueFISP scan (B).
Beyond the correct depiction of all stenoses and poststenotic lesions, MR-based assessment of prestenotic segments also revealed relevant lesions not depicted by conventional endoscopy. Two carcinomas, five polyps, and four segments with avid inflammatory chances were seen. Detection of metachronous colorectal carcinoma has an avid impact on further therapeutic strategies.

There are still no evident data about the impact of MR colonography on colorectal cancer screening. Because most colorectal cancers develop over a period of several years from adenomatous polyps, this pathogenesis makes colorectal cancer to a large extent preventable. Detection and removal of polyps eliminate the risk of subsequent malignant degeneration. Implementations of screening programs have been shown to reduce the incidence of colorectal cancer by more than 80% [35,36]. MRI actually includes all properties, which is necessary for a successful screening tool. The technique is not associated with any exposure to ionizing radiation and lacks any other known harmful side effects. Because of its noninvasive character, patient acceptance is not negatively impacted. Although MRI has been found to be an accurate means for the depiction of relevant colorectal masses (larger than 5 mm), we must be aware that these results were based on trials performed in preselected patient cohorts. Further studies are needed to evaluate the value of MR colonography in a screening population.

MR colonography has been applied successfully in patients with inflammatory bowel disease (Figs. 8, 9). Endoscopy in conjunction with biopsy has been considered the gold standard for the assessment of inflammatory bowel diseases [37,38]. Different studies have reported on the ability of MRI to detect and quantify inflammatory bowel disease [39–42]. Ajaj and colleagues [41] examined 23 patients with suspected inflammatory bowel disease of the large bowel by means of MRI. Inflammatory changes were documented and quantified according

![Figure 8](image-url)

**Fig. 8.** Patient with known Crohn’s disease and inflammatory lesions in the terminal ileum (arrowhead) and the transverse colon (arrow) with high contrast enhancement of the bowel wall and substantial lumen narrowing.
to four criteria: (1) bowel wall contrast enhancement, (2) bowel wall thickness, (3) loss of haustral folds, and (4) presence of perifocal lymph nodes. An MR colonography-based inflammation score was calculated. In this study, MR colonography correctly identified more than 90% of the colonic segments with inflammatory bowel disease changes. All severely inflamed segments were correctly described as such. MR colonography may be used for monitoring inflammatory bowel disease activity or assessing therapeutic effectiveness. Schreyer and colleagues [43] also evaluated MR colonography for the depiction of inflammatory bowel disease. In their trial, however, MR colonography failed to depict most subtle inflammatory changes, mainly in patients with Crohn’s disease. Severe inflammation was depicted by MR colonography with high accuracy. Beyond the depiction of inflammatory processes in the bowel wall itself, the presence of extramural changes, such as abscesses, often can be found. Fistulae or conglomerate tumor formations can be detected easily by means of MRI, whereas most of these extraintestinal findings are often not even suspected on endoscopy [44].

Strategies to enhance patient acceptance

In most centers, optical colonoscopy has emerged as the principal means to examine the large bowel. It offers the advantage of examination and biopsy or polyp removal but has multiple disadvantages. Procedural discomfort that results in the need for patient sedation and a small but defined risk for perforation results in a limited patient convenience [45]. Patient acceptance is one main issue for a screening test [9,10]. Virtual MR colonography still requires bowel cleansing in a manner similar to colonoscopy, because fecal matter can mimic the ap-

Fig. 9. T1-weighted contrast-enhanced image of a patient with chronic ulcerative colitis, which is shown by the loss of haustral markings in the sigmoid colon (arrow).
pearance of colonic masses. Because 75% of patients who undergo bowel preparation complain about symptoms that range from feeling unwell to inability to sleep [46], patient acceptance is negatively impacted. Further investigations underline the negative impact of the bowel purgation on patient acceptance [47], so bowel cleansing should be eliminated to ensure high patient acceptance of MR colonography. The cleansing can be achieved with fecal tagging—a concept based on modulating the signal intensity of fecal material by adding contrast compounds to regular meals. The signal intensity of stool is adapted to the signal properties of the rectal enema, and fecal material becomes virtually invisible.

A highly concentrated barium sulfate solution has been proposed for fecal tagging, which is administered in a volume of 200 mL with each of four principal meals beginning 36 hours before MR colonography [48–50]. Barium sulfate includes excellent properties as a tagging agent: it is not absorbed, it mixes well with stool, and allergic reactions after the ingestion are unknown. Fecal tagging with barium was used successfully in a volunteer study [48]. The study showed that ingestion of barium sulfate before the MR examination leads to a low signal of stool on T1-weighted gradient echo images, which renders fecal material virtually indistinguishable from the administered water enema (Fig. 10). A diagnostic image can be obtained for dark lumen MR colonography. A recent study revealed that patient acceptance was not increased by using barium-based fecal tagging instead of bowel cleansing procedures, because the ingestion of the tagging agent was considered as unpleasant as bowel purgation. Ongoing studies are being conducted for the evaluation of new tagging formulas [51].

Fig. 10. Fecal tagging–based MR colonography without bowel cleansing. The ingestion of a barium-containing contrast agent leads to a homogenous low signal intensity of the stool on the T1-weighted images (A). A solid depiction of the bowel wall is possible. Presence of fecal material is proved on the corresponding TrueFISP images (B), in which it impresses as dark filling defects within the bright colonic lumen.
Summary

The value of MR colonography has been well established. The most relevant advantages over conventional colonoscopy relate to the lack of procedural pain and discomfort. MR colonography enables image interpretation not limited to the endoscopic perspective. The diagnostic evaluation for other pathologic conditions that affect the colonic wall (eg, inflammatory diseases) benefits from this approach. Other extraintestinal organ systems contained within the imaging volume also can be assessed. There are some limitations to virtual colonoscopy based on MRI, however, including the inability to detect small lesions and the lack of therapeutic options.

References


