review

Computed tomography and magnetic resonance colonography

Sandra Vegar-Zubović, Irmina Sefić-Pašić, Lidija Lincender, Dunja Vrcic, Melika Klancevic, Una Delic

Institute of Radiology, Clinical Center University of Sarajevo, Bosnia and Herzegovina

Background. *Colon cancer is the second leading cause of cancer death in the western world. Adenomatous colorectal polyps, which are found in 30-50% of Americans more than 50 years old, are recognized as important precursors of malignancy. Probably most of the invasive colon carcinomas arise from polyps. For this reason an early detection of these polyps and their complete removal is a recognized strategy for the prevention of colon cancer. So far no single method for an early diagnosis of colon polyps or colon cancer offers high sensitivity and specificity along with low cost and good patient acceptance. Endoscopic colonoscopy allows the accurate detection of very small lesions and has since almost completely replaced fluoroscopy. Cross-sectional imaging techniques, including magnetic resonance imaging (MRI) and computed tomography (CT), are increasingly being considered imaging modalities for the detection of colorectal polyps.*
Conclusions. *CT and MR colonography are new techniques for imaging of the colon. In symptomatic patients, these new techniques show promising results for the detection of polyps equal to or larger than 1 cm in diameter.*

Key words: colonic neoplasms-diagnosis, tomography, X-ray computed; magnetic resonance imaging

Introduction

Colon cancer is the second leading cause of cancer death in the western world.[1] Several risk factors predispose a person to develop colon cancer.[2] Adenomatous colorectal polyps, which are found in 30-50% of Americans more than 50 years old, are recognized as important precursors of malignancy. Probably most of the invasive colon carcinomas arise from polyps. An early polyp removal has been shown to reduce mortality from colon cancer by 25-50%. For this reason the early detection of these polyps and their complete removal is a recognized strategy for the prevention of colon cancer.[3,4] So far no single method for an early diagnosis of colon polyps or colon cancer including faecal occult blood testing (FOBT), proctosigmoidoscopy, double contrast barium enema (fluoroscopy) or conventional endoscopy offers high sensi-

tivity and specificity along with low cost and good patient acceptance. Endoscopic colonoscopy allows the accurate detection of very small lesions and has almost completely replaced fluoroscopy. Furthermore, biopsies are easily harvested and polypectomy is also feasible. Although providing means for an early diagnosis of colon polyps and therapeutic intervention, endoscopic colonoscopy is a costly procedure which depends on the skill of the examiner and carries a low but not negligible risk of bowel perforation. Therefore, the indication to perform colonoscopy should be restricted to symptomatic patients or persons with an increased risk of cancer development. Furthermore, colonoscopy fails to reach the caecum in 5-10% of average risk-patients and in even higher percentages of patients with obstructing cancer.[5]

Cross-sectional imaging techniques, including magnetic resonance imaging (MRI) and computed tomography (CT), are increasingly being considered imaging modalities for the detection of colorectal polyps.[6,7] Using thin section axial images and assigned software both techniques allow the generation of three-dimensional views of the colon, simulating those obtained with conventional colonoscopy. Since CT-colonography is relatively safe and minimally invasive, it has the potential to become an attractive alternative to existing tests for an early diagnosis of colorectal cancer.[8]

Major advantages over endoscopy are its shorter examination time, non-invasiveness, and relative independence from the examiner. Thus, patient acceptance for this new method may be improved. Inherent advantages of CT-colonography, compared to endoscopy, include the visualization of the colon proximal and distal to constricting lesions, the ability to quantify local morphometric characteristics of the colon such as wall thickness and tumour extension in the extraluminal space, and the accurate localization of other abnormalities. It has to be stressed, however, that CT-colonography requires bowel cleansing and bowel distension by air insufflation similar to barium enema or conventional colonoscopy. Therefore, the patient's discomfort still remains a problem. Currently MRI CT-colonography is restricted by limited availability of scanners and high procedural costs. MRI as well as single-slice CT suffers from restrictions in spatial resolution and from motion artefacts, which explain insufficient detection rates for masses smaller than 10 mm.[6,7]

Single-slice CT requires several breath holds or a slice thickness exceeding 4 mm in order to scan the entire colon. A recent study comparing single-slice CT-colonography and conventional colonoscopy suggests a similar efficacy for the detection of polyps 6 mm or more in diameter (82-91%). However, restrictions in spatial resolution resulted in a low sensitivity for polyps smaller 6 mm (55%) and frequent false positive findings.[6] Recently introduced multi-slice CT (MSCT) scanners represent a significant improvement in CT technology, combining high-resolution thin slice imaging with high-speed volume coverage,[9] resulting in multiple advantages over single-slice-CT which has been documented for CT-angiography or lesion detection in the liver.[10,11] MSCT has already been shown to enhance the quality of CT-colonography due to the improved colonic distension and reduction of respiratory motion artefacts compared to single slice CT.[12]

Methods of colon investigation

Currently, there are four methods for the investigation of the entire colon. These are double-contrast barium enema (DCBE), colonoscopy, CT colonography, and MR colonography. Fischer described the DCBE technique in 1923.[13] It was refined in the

late 1960s and became the radiologic technique of choice for colon imaging in the mid-1970s.[14,15] Recently, the DCBE technique was reviewed.[16] It was concluded that performing a high-quality DCBE study requires tailoring of the examination to the clinical history, patient, and fluoroscopic findings. Each colonic segment should be viewed in detail with spot radiographs or magnified digital images. The order in which these are obtained is flexible, as long as each loop of colon has adequate barium coating and distention and is demonstrated en face. Overhead views such as left and right side–down *decubitus* views and a prone-angled view of the rectosigmoid junction are helpful in piecing together the spot images.[16]

Colonoscopy was first described in 1965 by three independent Japanese groups in the same journal.[17-19] Since then, technical developments made scopes smaller, easier to manipulate around angles, and improved the quality of the visualization methods.

Compared to DCBE studies and colonoscopy, CT and MR colonography (MRC) have a short history and are still being developed. CT colonography was described in 1994 by Vining *et al.*[20] and MR colonography in 1997 by Luboldt *et al.*[21] Both are cross-sectional methods that generate numerous images in the axial plane (CT) or any desired plane (MR imaging), preferably during one breath-hold. To efficiently read these images, postprocessing on a workstation is necessary. Such workstations should be able to handle the data quickly and, therefore, should have adequate hardware and software to allow fast interaction with the data set. These data sets can consist of up to 700 images with relatively high spatial resolution.

Reading the source images is the first step. These images need to be viewed carefully for filling defects and, if applicable, enhancing lesions. Postprocessing is an important feature of image interpretation. The most simple and important postprocessing technique for CT and MR colonography is multiplanar reformatting (MPR).[22,23] Furthermore, volume rendering techniques, such as tissue transition projection or endoscopic three-dimensional (3D) viewing (virtual endoscopy), can be performed. These require a great deal of computer power; endoscopic 3D viewing is especially time-consuming. Other 3D rendering techniques such as maximum-intensity projection (MIP) and shaded surface display (SSD) are easy to perform but only a small part of the entire data set is used in these techniques. Thus, much important information is lost and this makes these techniques unsuitable for the polyp detection. Postprocessing techniques will be discussed in detail. The purpose of this article is to describe scanning techniques in CT and MR colonography, discuss the currently available postprocessing methods, and discuss the accuracy of these techniques for the polyp detection compared with colonoscopy and DCBE.

CT colonography

Computed tomography (CT) colonography (virtual colonoscopy) is a promising new method for detecting colorectal polyps and cancers. Although multiple articles on this issue have been published since the mid-1990s, it remains an important discussion topic in current radiology and gastroenterology societies. Regarding its clinical role, there is no doubt that this imaging technique is best suited and highly recommended for those patients who are unable or unwilling to undergo conventional colonoscopy. Its role as a general screening tool for colon cancer is obvious for many, equivocal for some, and doubtful for others.

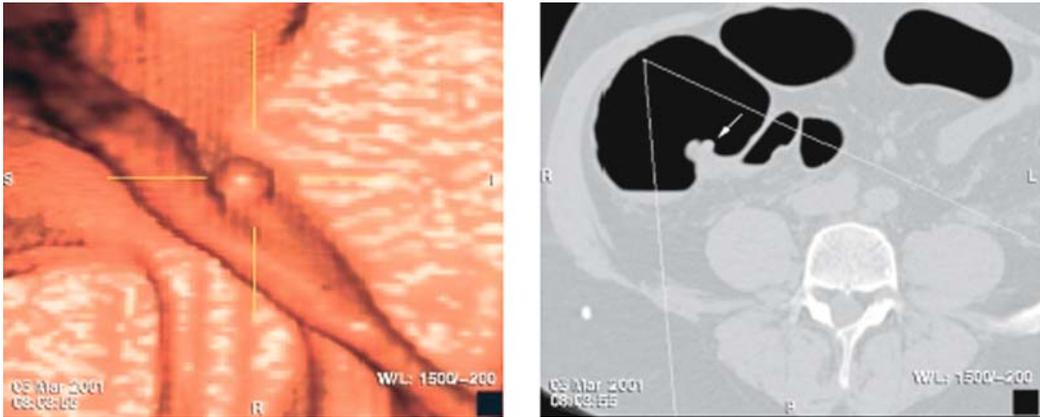CT colonography uses multidetector-row CT to generate data, which is then

Figure 1. Multislice CT colonography.

converted by computer software into 2-dimensional (2D) and 3-dimensional (3D) displays of the colon. CT colonography has several advantages over conventional colonoscopy: No sedation is needed, it is only minimally invasive, and the examination is less time-consuming than conventional colonoscopy. However, there is still a need for bowel cleansing and insufflation of gas to expand the colon. Moreover, exposure to radiation is inherent to CT, and there is no possibility of biopsy, polypectomy, or treatment during the examination (Figures 1, 2).

MSCT has the potential to significantly improve the detection rate for colorectal polyps due to its better z-axis resolution, improved 3D-image quality and faster data acquisition. The detection and the subsequent removal of colorectal polyps remain the most important approaches for the reduction of colon cancer related mortality (Figures 3, 4, 5).

Studies

A meta-analysis of data from 14 studies with a total of 1324 patients reported the sensitivity and specificity of CT colonography for the detection of polyps, using conventional colonoscopy as the reference standard. The pooled per-patient sensitivity for polyps 10 mm or larger was 88% (95% confidence interval [CI], 84–93%), for polyps 6–9 mm it was 84% (95% CI, 80–89%), and for polyps 5 mm or smaller it was 65% (95% CI, 57–73%). The pooled per-polyp sensitivity for polyps 10 mm or larger was 81% (95% CI, 76–85%), for polyps 6–9 mm it was 62% (95% CI, 58–67%), and for polyps 5 mm or smaller it was 43% (95% CI, 39–47%). The overall specificity for the detection of polyps 10 mm or larger was 95% (95% CI, 94–97%).

A study involving 1233 asymptomatic adults reported that the per-patient sensitivity for polyps 10 mm or larger was 94% (95% CI, 83–99%) for CT colonography and 88% (95% CI, 75–95%) for conventional colonoscopy. The per-patient sensitivity for polyps 6 mm or larger was 89% (95% CI, 83–93%) for CT colonography and 92% (95% CI, 87–96%) for conventional colonoscopy.

A study of 615 patients reported per-patient sensitivities of 55% (95% CI, 40–70%) for polyps 10 mm or larger and 39% (95% CI, 30–48%) for polyps 6 mm or larger. Another study of 614 patients reported that CT colonography was significantly more sensitive than barium enema but less sensitive than colonoscopy.
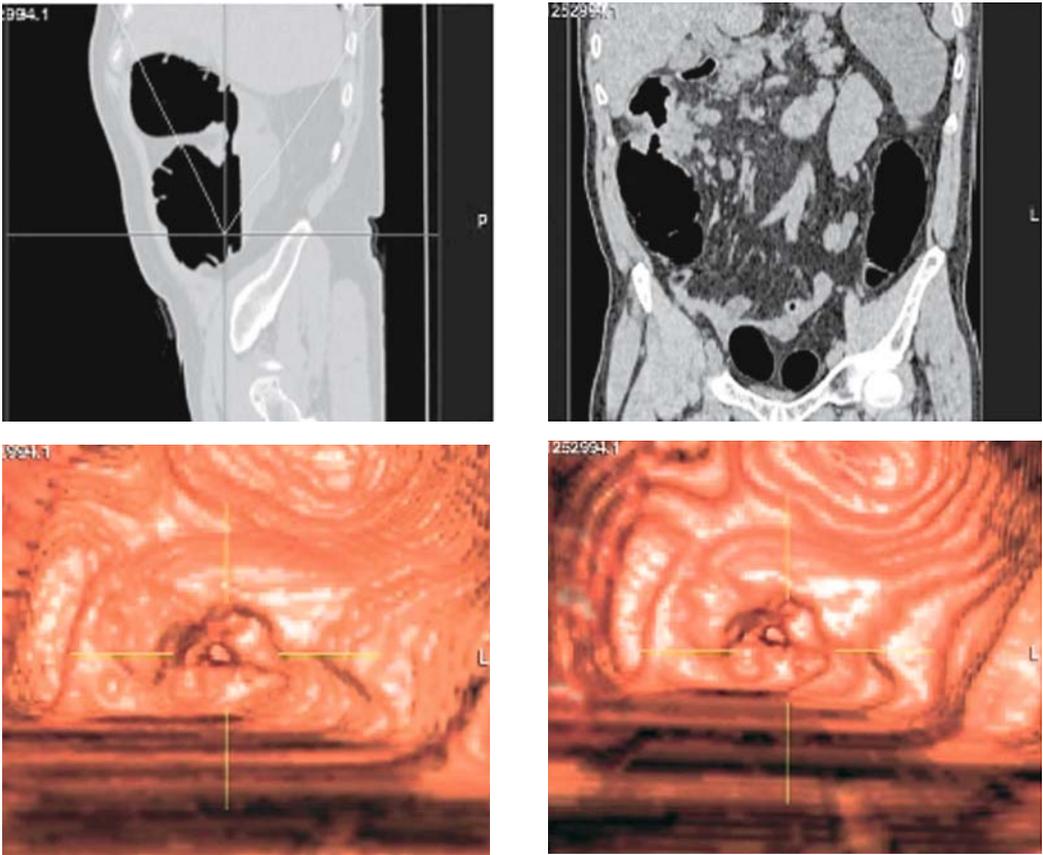
Figure 2. Multislice CT colonography. Colon tumour in 67-year old patient.

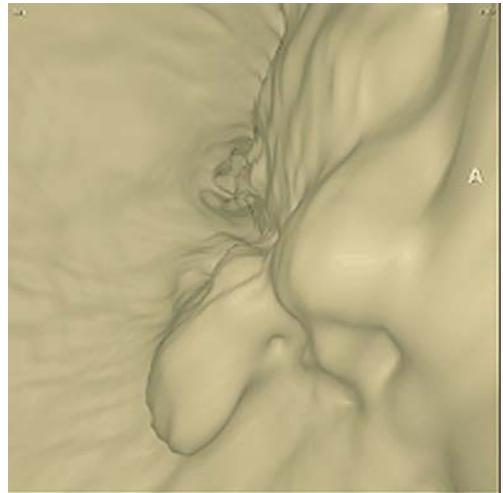**Figure 3.** Shaded surface display of inflammatory stenosis.

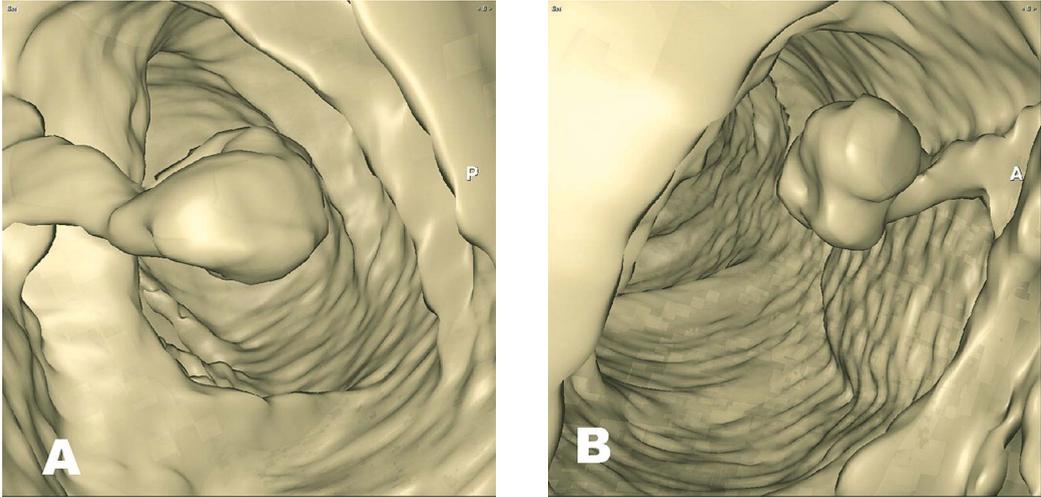**Figure 4.** Virtual colonoscopic view of polypoid lesion.

Figure 5. Virtual colonoscopy. (A) Retrograde and (B) antegrade views of polyp.

A study of 203 patients that used faecal tagging reported an overall per-patient sensitivity of 90% (95% CI, 86–94%).[24]

MR colonography

Currently two techniques are being evaluated for MR colonography . Based on the signal within the colonic lumen, they can be differentiated as "bright lumen" and "dark lumen" MRC (Figure 6).

Bright lumen MRC

Similar to contrast enhanced 3D MR angiography, MRC is based on the principles of ultra fast, T1 weighted 3D GRE acquisitions collected within the confines of a single breath hold.[25] This requires the use of an MR scanner equipped with high performance gradients. To permit the homogenous signal transmission and the reception over the entire colon with high CNR values, a combination of phased array surface coils should be used. The size of the coil must permit a coverage of the entire colon. As

colonic lesions can often not be differentiated from stool, the patient has to undergo bowel cleansing in a manner similar to that required for conventional colonoscopy. Before the examination the patient should be screened for contraindications to MRI such as severe claustrophobia, presence of metallic implants in critical regions such as the eyes, spinal chord or brain, or cardiac pacemakers. The presence of hip prostheses, which normally is not regarded a contraindication to MRI, impedes a complete analysis of the rectum and sigmoid colon. Therefore, patients with hip prosthesis should also not be examined by MRC.

After the placement of a rectal enema tube, the colon is filled with the patient in the prone position using 1000 to 2000 ml of a water based enema, spiked with paramagnetic contrast (1:100). The enema is administered using 100 cm–150 cm of hydrostatic pressure. To reduce bowel motion and alleviate colonic spasm, the use of intravenously administered spasmolytic agents (for example, scopolamine or glucagon) before and during the bowel filling is helpful. In contrast with conventional colonoscopy sedative or analgesic agents do not have to

be applied. To ensure safe and optimal bowel filling and distension, the filling process is monitored with a non-slice select 2D acquisition, collecting one image every three seconds. Once the enema has reached the *caecum*, a 3D dataset of the abdomen encompassing the entire colon is collected. To compensate for the presence of residual air exhibiting "filling defects" similar to polyps within the colonic lumen, 3D datasets are collected in both the prone and supine patient positions. Here-after the enema bag is placed on the floor for facilitated emptying of the colon and the patient is removed from the scanner.

The acquired 3D MR datasets consist of coronal sections, ranging in thickness between 1.5 mm and 2 mm. The sequence is based on the use of short repetition (TR 1.6 ms–3.8 ms) and echo times (0.6 ms – 1.6 ms). The achievable minimum TR should be shorter than 5 ms; otherwise, the acquisition of a 3D dataset cannot be collected within the confines of a single breathhold. In conjunction with a field of view of 400 x 400 mm and an imaging matrix of 460 x 512, the spatial resolution includes an interpolated voxel size of about 1 mm x 1 mm x 1.6 mm.

On the 3D GRE datasets only the colonic lumen containing the enema is bright, whereas all other tissues remain low in signal intensity. The resulting contrast between the colonic lumen and surrounding structures is the basis for the subsequent virtual colonographic viewing. The MRC protocol can be further amplified by the acquisition of 2D gradient echo datasets after the intravenous application of a gadolinium containing contrast compound. This permits a more comprehensive assessment of parenchymal abdominal organs and increases the ability to detect hepatic metastases.

Bright lumen MRC can be completed within 20 minutes, including the time for patient positioning, image planning, and data acquisition. The 3D datasets are subsequently processed using commercially available software and hardware. A complete analysis of an MRC examination still requires 15 minutes of interactive image viewing on a high performance work station. In the first step MRC images should be interpreted in the multiplanar reformation mode scrolling through the prone 3D dataset in all three orthogonal planes. In regions containing larger pockets of residual air, the assessment needs to be supplemented by views of the supine dataset. In the second step the data should be assessed based on virtual endoscopic renderings displaying the inside of the colonic lumen. A virtual endoscopic fly through allows the observer to concentrate on the colon facilitating the depiction of small structures protruding into the colonic lumen. Furthermore, the three dimensional depth perception permits the assessment of haustral fold morphology, thereby increasing the observer's ability to distinguish polyps from haustra. To assure the complete visualisation of both sides of haustral folds, the virtual fly through should be performed in an antegrade as well as retrograde direction.

Dark lumen MRC

The detection of colorectal lesions with "bright lumen" MRC relies on the visualisation of filling defects. Differential considerations for such a filling defect beyond polyps include air bubbles as well as residual faecal material. To permit differentiation datasets are collected in both the prone and supine patient position: air and faecal material move, while polyps remain stationary. While effective in most instances, the technique can introduce errors. Thus, polyps with a long stalk may move sufficiently to impress as a moving air bubble or more probably residual stool, while stool adherent to the colonic wall may not move at all and, thus,

falsely impress as a polyp. In addition to obviating the need for the second, time consuming 3D data acquisition "dark lumen" MRC facilitates the identification of polyps.

"Dark lumen" MRC focuses on the colonic wall. It is based on the contrast generated between a brightly enhancing colonic wall and a homogeneously dark colonic lumen.[26] The technique differs from "bright lumen" MRC in the following manner:

1. Instead of gadolinium containing enema only tap water is rectally applied rendering low signal on heavily T1 weighted 3D GRE acquisitions.
2. The colonic filling process is monitored with a fluoroscopic T2w sequence, rather than a T1w sequence.
3. To obtain a bright colonic wall paramagnetic contrast is applied intravenously. 3D datasets are collected before the application and after a 75 second delay.
4. As residual air exhibits no signal in the colonic lumen, the examination needs to be performed only in the prone patient position.

Compared with "bright lumen" MRC that has been extensively evaluated in the past, "dark lumen" MRC harbours considerable advantages including the reduced examination and post-processing times, as only one 3D dataset needs to be collected. Furthermore, the "dark lumen" technique copes with the problem of residual stool in a simple manner: if the lesion enhances, it is a polyp; if it does not enhance, it represents stool. Suspicious appearing lesions are analysed by comparing signal intensities on the pre-contrast and post-contrast images. If analyses were limited to the post-contrast dataset, bright stool could be misinterpreted as a polyp. A comparison with the pre-contrast images records the lack of contrast enhancement, which assures the correct diagnosis.

The enhancement of colorectal masses following the intravenous administration of contrast has been reported in conjunction with MRC[22] and CT colonography.[23] The use of intravenously administered contrast material significantly improves the reader confidence in the assessment of bowel wall conspicuity and the ability to depict medium sized polyps in suboptimally prepared colons. The enhancement observed within polyps exceeds the increase determined within the colonic wall. This may aid in differentiating even very small polyps from thickened haustral folds.

A further advantage of "dark lumen" MRC relates to the fact that it permits a direct analysis of the bowel wall. This might facilitate the evaluation of inflammatory changes in patients with inflammatory bowel disease. Increased contrast uptake and bowel wall thickening, as recorded on contrast enhanced T1 weighted images, have already been shown to correlate well with the degree of inflammation in the small bowel.[27] Hence, the "dark lumen" approach may indeed amplify the list of indications for MRC in the future to encompass also inflammatory bowel disease.

Finally, the intravenous application of paramagnetic contrast permits a more comprehensive assessment of parenchymal abdominal organs contained within the field of view. By combining pre-contrast and post-contrast T1 weighted imaging, the liver can be accurately evaluated regarding the presence and type of concomitant disease. Dark lumen MRC also offers new perspectives regarding the optimisation of bowel distension. Although the administration of water as a rectal enema does not adversely affect patient comfort in most cases, a modified strategy could be based on the application of gases like carbon dioxide.[28] The gas is signalless and would thus easily permit delineation of the contrast enhanced colonic wall and masses.

The diagnostic performance of bright lumen MRC was assessed in several stu-

Table 1. Sensitivity and specificity of bright lumen MR colonography (MRC)[29]

All lesions	
Sensitivity	27/58 = 47%
Specificity	48/59 = 81%
PPV	27/38 = 71%
NPV	48/79 = 61%
Lesions >10 mm	
Sensitivity	13/14 = 93%
Specificity	102/103 = 99%
PPV	13/14 = 93%
NPV	102/103 = 99%

PPV = Positive predictive value
NPV = Negative predictive value

dies using conventional colonoscopy as the standard of reference. While most mass lesions smaller than 5 mm in size were missed, almost all lesions exceeding 10 mm were correctly identified (Table 1).[29] In a study by Pappalardo *et al.* MRC even detected a higher total number of polyps exceeding 10 mm in size than conventional colonoscopy. MRC identified additional polyps in regions of the colon not reached by colonoscopy (Figure 6).
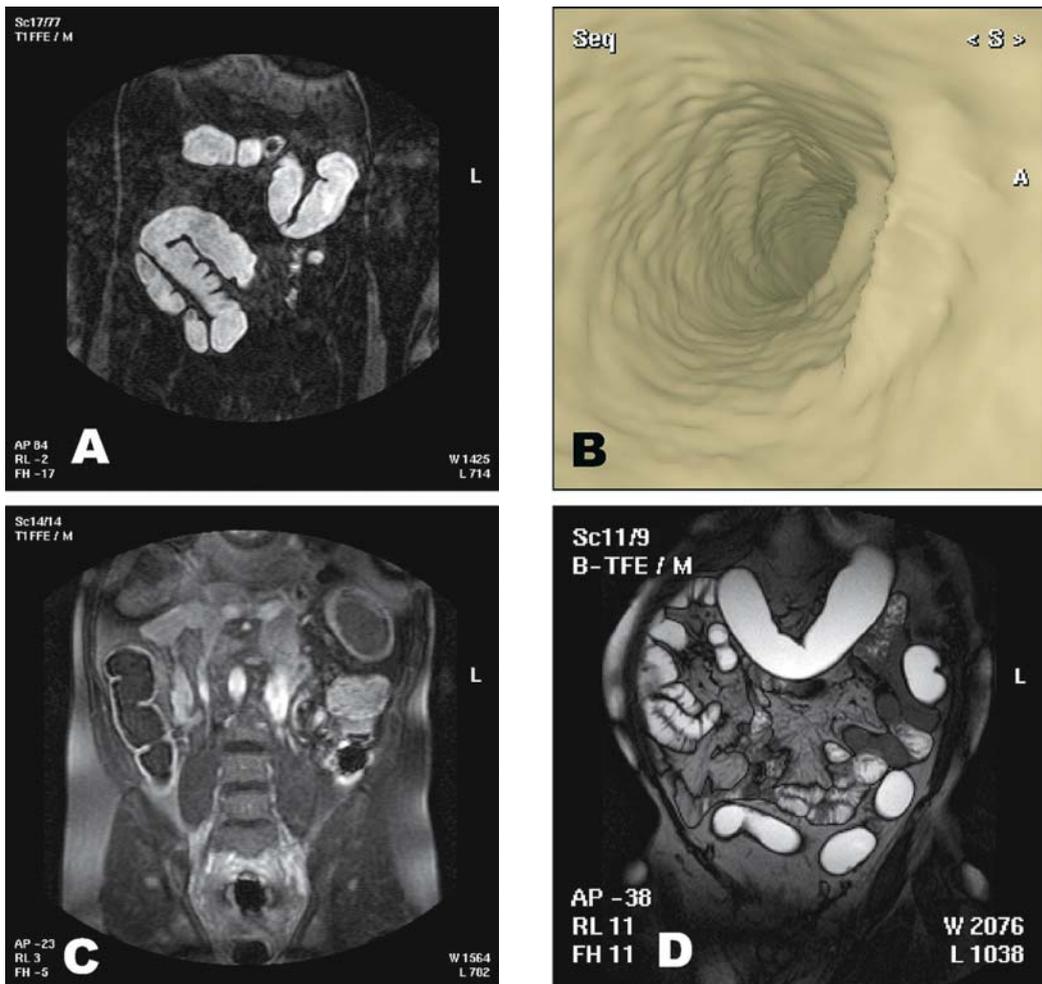

Figure 6. MR colonography. A, Bright lumen technique: 3D GRE sequence with water-gadolinium enema. B, Virtual colonoscopy of normal ascending colon. C, D, Combined bright and black lumen technique: C, contrast-enhanced 3D spoiled T1-weighted GRE image and, D, nonenhanced 3D spoiled and balanced GRE image.

Faecal tagging

MRC still requires bowel cleansing in a manner similar to conventional colonoscopy. As 75% of patients undergoing bowel preparation complain about symptoms ranging from "feeling unwell" to "inability to sleep", patient acceptance is affected negatively. To assure high patient acceptance of MRC, bowel cleansing needs to be eliminated. This can be accomplished with faecal tagging—a concept based on modulating the signal intensity of faecal material by adding contrast compounds to regular meals.

Fitting the two approaches to MRC (bright lumen and dark lumen); there are also two theoretical approaches to faecal tagging. Its principle was demonstrated on the basis of a bright rectal enema distending the colonic lumen containing brightly tagged stool in conjunction with bright lumen MRC. By adding a T1 shortening Gd based MR contrast agent to regular meals before the MR examination, harmonisation of signal properties between faecal material and the Gd based enema was achieved. The oral administration of a paramagnetic MR contrast agent (Gd-DOTA) has been shown to be safe. The combination of faecal tagging with a paramagnetic contrast agent and colonic filling results in a homogenous signal distribution throughout the colon. In these examinations virtual MRC permits an unobstructed view through the colon because the tagged stool is virtually indistinguishable from the administered enema. Although encouraging results concerning acceptance and image interpretation were obtained, the clinical implementation of bright lumen faecal tagging was hindered by the high cost of the Gd based paramagnetic contrast agent.

A second strategy for faecal tagging is based on rendering the colonic lumen dark. For faecal tagging, a highly concentrated, barium sulphate containing contrast agent (Micropaque; Guerbet, Sulzbach, Germany; 1 g barium sulphate/ml) is administered in a volume of 200 ml with each of four main meals beginning 36 hours before MRC. Patients are instructed to avoid the intake of all fibre rich foodstuff and nourishments with high concentration of manganese such as chocolate or fruits during this period, as manganese leads to increased signal intensity in T1w sequences. "Barium based" faecal tagging is combined with dark lumen MRC: the colon is distended with a rectally applied water enema and paramagnetic contrast is administered intravenously to render the colonic wall and adherent colorectal mass lesions bright.

Barium sulphate is a well known diagnostic contrast agent, still in common use as an oral agent for oesophageal, gastric, and small bowel radiography. Compared with Gd based contrast compounds, it is far less costly and characterised by an even better safety profile. Anaphylactoid reactions or other adverse side effects are virtually unknown. The agent is not absorbed and mixes well with stool. Thus, barium includes all characteristics as an ideal oral tagging agent for MRC.

The barium based approach to faecal tagging has been successfully assessed. The signal reducing effects upon stool has been documented in volunteer studies. By ingesting barium before the MR examination, stool is rendered virtually indistinguishable from the administered water enema on heavily T1w 3D GRE image. The MR examination without the prior ingestion of barium reveals signal rich stool that cannot readily be differentiated from the brightly enhancing colonic wall.

Recently, the barium based faecal tagging concept has been successfully evaluated in a pilot patient study. Faecal tagged MRC detected all polyps larger than 8 mm in a population of 24 patients with known

or suspected colorectal tumours. The overall sensitivity of MRC amounted to 89.3% for the detection of colorectal masses, and specificity was 100%. Colorectal cancers and polyps were readily identified as such.

Although further work is required to confirm these excellent results, it seems that barium tagged MRC has vast potential to emerge as the examination strategy of choice for the early detection of polyps in asymtomatic subjects. The technique seems to combine the excellent diagnostic accuracy with the high patient acceptance based on a painless examination and no need for colonic cleansing.

Conclusions

In conclusion, CT and MR colonography are new techniques for imaging of the colon. In symptomatic patients, these new techniques show promising results for the detection of polyps equal to or larger than 1 cm in diameter. It must be remembered that in all research protocols, colonoscopy was considered to be the standard of reference, which implies that other imaging modalities with which colonoscopy is compared will always perform worse. In most studies, patients preferred CT colonography to conventional colonoscopy.

The bowel-cleansing regimen is considered to be cumbersome, so from the patient acceptance point of view, faecal tagging techniques are promising. Their value in polyp detection still needs to be determined in large studies. In medicine, there is a trend toward performing non-invasive or less invasive imaging techniques rather than older and more validated invasive techniques. (MR angiography or CT angiography *vs* digital subtraction angiography, MR cholangiopancreatography *vs* endoscopic retrograde cholangiopancreatography). The invasive techniques are used for

problem solving and interventions. CT and MR colonography fit in this trend perfectly. Both techniques have shown promising initial results in symptomatic patients and are still in evolution. Before these techniques can be implemented in daily practice, they must show the same accuracy as colonoscopy and should be cost-effective in both high-risk and screening patients.

The radiation-dose issue in CT colonography must be discussed, and a consensus on the maximum acceptable dose for a screening patient must be reached. MR colonography has the advantage of being a zero-dose examination, but at this point, CT colonography is faster and provides images with higher resolution.

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