3-D Modeling and Virtual Endoscopy of the Small Bowel Based on MR Imaging in Patients with Inflammatory Bowel Disease

*Investigative Radiology 2002;37(9):528-533*

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Acknowledgment: The work was supported by DCCV e.V., Leverkusen, Germany (German Crohn's Disease and Ulcerative Colitis Association)
Abstract:

Rationale and Objectives:
Small bowel MRI (Magnetic Resonance Imaging) is a new imaging modality which excellently depicts small intestine pathology in patients with inflammatory bowel disease. Virtual endoscopy based on sectional imaging is a recently introduced technique to create endoscopy like views. The aim of this study was to evaluate the feasibility of virtual small bowel endoscopy based on MR imaging in patients with Crohn's disease.

Methods:
Thirty consecutive patients with Crohn's disease were scanned after oral application of pineapple juice for contrasting the small bowel. Dedicated high resolution T1 weighted 3D-FLASH sequences with fat suppression were employed for volume scanning. Volume rendered three-dimensional models of the small bowel were created and virtual endoscopy was performed. The feasibility and quality of this new visualization method was assessed.

Results:
In 9 of 30 patients virtual endoscopy was considered as ‘good’ quality (flight through the entire small bowel was possible, typical folds were revealed). In 18 patients fair quality (at least 4/5 of the small bowel were depicted adequately) was assessed. In 3 of 30 patients virtual endoscopy was not sufficiently possible because of inadequate bowel filling or breathing artifacts. Three fistulae diagnosed on 2D MRI were visualized on the virtual endoscopic view.

Conclusion:
Virtual endoscopy of the small bowel is feasible based on high resolution MR imaging. Vivid insight views and 3D models provide an interesting addition to sectional MR findings.

Key Words:
MRI, Virtual Endoscopy, Volume Rendering, Small Bowel, Crohn's Disease
INTRODUCTION

Patients with inflammatory bowel disease (IBD) undergo numerous diagnostic examinations of the gastrointestinal tract during the course of their chronic disease. Conventional colonoscopy for assessment of the colon and small bowel enteroclysis are methods of choice for intestinal examinations. The small bowel, which is frequently affected in patients with IBD, is currently examined applying x-ray based radiological methods.

Although enteroclysis is currently performed as a routine examination for depicting the small bowel, the examination is fairly unpleasant and has a significant radiation dose for the mostly young patients. A replacement of this examination would be much desirable.

Spiral CT allows volume acquisitions of the whole abdomen within one breath-hold. It is considered as an adequate technique for diagnosis of extraluminal complications in patients with IBD. CT, however, causes at least the same amount of radiation as conventional enteroclysis.

MR imaging of the abdomen and bowel became available recently due to the introduction of ultrafast gradients and fast sequences. This new technique allows scanning of the entire abdomen within one breath-hold, which is a prerequisite for bowel diagnostics. Different groups are postulating the diagnostic efficiency of MRI examination for stenoses, fistulae and inflammation of the small intestine.

One important problem in small bowel assessment remains the confusing anatomy of the long bowel loops, which are tortuously stacked together in the abdomen. With x-ray based conventional enteroclysis several over-projections occur. On sectional image modalities such as CT and MR it is difficult to follow particular bowel loops through all the slices.

Employing recently introduced 3D (three dimensional) visualization techniques may help understanding the complex small bowel anatomy. In this study we demonstrate the feasibility of 3D small bowel visualization combined with small bowel enteroscopy. Applying virtual endoscopy techniques based on MR imaging we illustrate the intraluminal findings of small bowel anatomy and pathology in vivo.
MATHERIALS AND METHODS

Patients
As part of an ongoing study on MR-enteroclysis in patients with inflammatory bowel disease (IBD) 30 consecutive patients (14 females, 16 males; ranging 17 to 55 years, mean 24 years) with Crohn's disease were assigned prospectively for this trial. The inclusion criteria was the diagnostic need for a small bowel examination in adult patients without any contraindications for MR imaging. Conventional small bowel enteroclysis was performed for diagnosis and disease assessment of IBD (n=12) or as follow up examinations (n=18) in symptomatic patients. The study protocol was approved by our institutional review board, and written informed consent was obtained from all patients.

Enteroclysis
In all patients enteroclysis with double contrast was performed as an established method for small bowel diagnosis.
After transnasal intubation past the duodeno-jejunal junction the examination was performed with barium followed by methylcellulose as described15-17.

MR Imaging
MR imaging was done in all patients 24 to 48 hours before or after enteroclysis. None of the patients was examined on the same day because of potential MR signal alterations caused by barium18.
For contrasting the bowel lumen we mixed 1.5 liters of regular pineapple juice, which is commercially available, with 20 g of methylcellulose. The fairly high natural manganese content of pineapple juice (12.7 mg/l) results in positive T1 weighted intraluminal small bowel contrast19-21. The positive intraluminal contrast was useful for creating 3D reconstructions and virtual endoscopy straightforwardly. The juice was ingested steadily over a 2 hours period prior to the MR examination. Imaging was performed in a 1.5T MR scanner unit (Symphony, Siemens Medical Systems, Erlangen) with 20 mT/m gradients. Using a circular polarized phased array body coil patients were scanned in prone position.
During the scan 20mg scopolamine (Buscopan®, Boehringer, Ingelheim, Germany) in 100 ml NaCl were given intravenously. As part of the experimental protocol fat suppressed 3D-FLASH was performed for 3D reconstruction. The scanning parameters for T1-weighted coronal images were TR/TE, 4.6/1.8 msec; flip angle, 25°; slab thickness, 140 - 160 mm with 80 partitions. A 512 X 210 matrix was applied with a FOV (field of view) of 400mm. The sequence gained a nearly isotropic voxel resolution of approximately 1.4mm to 1.7mm depending on the slab thickness. The breath-hold sequence was acquired within 28 seconds. Afterward 0.1 mmol/kg Gd-DTPD (Magnevist®, Schering, Berlin, Germany) was given intravenously. The reason for the i.v. contrast was another ongoing study which addresses T1-weighted signal enhancement correlating with inflammatory bowel reaction. Thus an additional 3D-FLASH sequence was obtained resulting in two complete 3D acquisitions before and after i.v. contrast enhancement in each patient.

3D Visualization

For creating 3D models and virtual endoscopy the 3D-FLASH data was transferred to an independent graphic workstation (O₂, Silicon Graphics, Mountainville, CA, USA) using an Ethernet connection. For 3D visualization the Virtuoso3D software (Siemens Medical Systems, Erlangen, Germany) was employed.

Volume rendering was used for 3D visualization and virtual endoscopy of the small bowel. This algorithm has the advantage of real time 3D representation without time consuming manual data segmentation. In the small intestine multiple bowel loops can be stacked very close together. This raises problems for an automated computer generated path planning. We therefore performed a manual approach. The user interface of the software allows to inspect the data in three different ways: An exterior view provides the general orientation, the virtual endoscopic view allows inspection of the interior bowel walls, and the cross-sectional images allow to assess the morphology below the surface (Fig. 1). Cross-reference between the 2D and the two 3D images is provided by a simple mouse interaction. The direction of movement through the bowel is based on such cross-references. Wherever the pointer moves, the virtual camera follows as well. The motion is calculated and executed in real time. Using this approach we started our interactive
virtual flight at the ileo-coecal valve flying through the ileum toward the jejunum. If possible, the flight ends in the duodenum or contrast medium filled stomach. The virtual camera is displayed as a corresponding point on the volume rendered external view and the original sectional image.

Considering the coronal 3D-FLASH data and the resulting virtual endoscopy the quality of the examination was subjectively assessed by a radiologist and an endoscopist in agreement. In order to evaluate the feasibility and quality of virtual small bowel endoscopy the readers were not blinded for the findings derived from the conventional and MRI enteroclysis. Two 3D-FLASH acquisitions were obtained for each patient before and after application of i.v. contrast. For each subject, the radiologist selected the best suited series, to use for the virtual endoscopy. The 3D-FLASH MR images were scored as good quality, fair quality or insufficient quality. Insufficient quality described series with motion artifacts or inadequate bowel fillings which do not have diagnostic quality. In fair series utmost 1/5 of the small bowel was not sufficiently depicted because of bowel motion artifacts or incomplete bowel contrast. Good quality characterizes virtual flights with adequate bowel filling and distension which even show particular small bowel fold patterns in the jejunum and ileum.
RESULTS

Using the 3D-FLASH acquisitions of 30 patients before and after i.v. Gadolinium 60 datasets for volume rendered 3D imaging (Fig. 2) and virtual endoscopy of the small bowel were evaluated. In 10% (3/30) of the patients not even one series accomplished sufficient image quality for 3D rendering (Table 1). In two patients motion and breathing artifacts occurred during the scan and one patient had inadequate small bowel filling because of inconstant ingestion of the pineapple juice. In 18 of 30 patients (60%) at least one series resulted in fair quality examinations for 3D modeling and virtual endoscopy. Most of the small intestine was depicted adequately while the contrast was fairly homogeneous and continuous. Virtual endoscopy in these patients revealed no typical small bowel patterns. The small bowel was depicted as a tubular structure whilst in conventional enteroclysis the small bowel of these patients showed regular folds. In 9 patients (30%) at least one series revealed good quality virtual flights. In this group typical intestinal fold patterns could be depicted within the jejunum (Fig. 3) and ileum. Solely in these patients a complete fly-through the small intestine was feasible.

The flight path through the small bowel had to be created manually. A complete flight through the small intestine took approximately 15 minutes (ranging from 10 to 20 min.) including rendering computation time and path planning. The closeness of the bowel loops made it sometimes difficult to stay within the correct lumen. The cross-reference between the sectional data and the endoscopic view proofed to be advantageous for maneuvering through the small bowel loops.

In 80% of the patients (24/30) normal anatomy without pathological changes was seen on virtual endoscopy. This corresponded to the findings of the conventional enteroclysis. In 3 patients fistulas between bowel loops were seen on MRI as well as with conventional enteroclysis. All fistulas were visualized with virtual endoscopy (Fig. 4). Another 3 patients had a significant narrowing of the terminal ileum on conventional enteroclysis. This was depicted impressively as a typical wall thickening and narrowing on the source MRI slices. The bowel narrowing was shown more obviously by the volume rendered 3D external view than by the endoscopic view (Fig. 5). Using the external view the length and grade of the stenosis could be judged three-dimensionally.
Currently there are no routinely used endoscopic techniques for visualization of the entire small intestine. Recently introduced small bowel enteroscopy, respectively push enteroscopy\(^22\) and sonde enteroscopy\(^23\) or wireless capsule endoscopy\(^24\) are methods for direct visualization of the small bowel wall. Push enteroscopy depicts only the first jejunal loop. Sonde enteroscopy and the novel wireless capsule enteroscopy are new remarkable techniques. However, they are unpleasant and cannot provide a complete view due to sudden propulsions of the capsule.

MRI seems to be a promising method for the diagnosis and follow up of patients with IBD\(^{13,14}\). It combines high soft-tissue resolution and objectivity of cross-sectional imaging with the lack of radiation and has no other known side effects. Moreover, MRI has a high sensitivity for the detection of relevant extraluminal pathology such as abscesses or fistulas\(^10\).

Several approaches have been reported for the application of contrast media and small bowel imaging using MRI. One method is to exploit the intraluminal fluid for contrast\(^{25,26}\). Additional drinking of tap water fills and distends the small intestine. Applying HASTE or True-FISP\(^{27}\) sequences, the fluid filled small bowel can be depicted adequately. This technique proved to be an excellent modality in the diagnosis of small bowel obstruction.

Another method is the application of negative contrast medium\(^28\). The bowel wall can be appreciated reasonably using this technique.

Recently the ‘dark lumen’ technique\(^29\) was introduced, which basically gains a black intraluminal signal with a high signal bowel wall based on i.v. contrast. The technique was employed for MRI colonography, other abdominal applications still have to be evaluated.

In our study we used positive T1 weighted intraluminal contrast to achieve 3D reconstructions and virtual endoscopy straightforwardly. Employing the natural high manganese content of pineapple juice resulting in high intraluminal T1 signal\(^20\) provided sufficient high resolution MRI data for 3D imaging. The 3D-FLASH sequence acquired isotropic resolution which is additionally advantageous for 3D image processing.
Recently introduced ultrafast high resolution sequences like 3D True FISP\textsuperscript{30} could be an interesting option in the near future.

A common problem in small bowel imaging appears to be the topographical assessment of pathological changes because of the complex and tortuous anatomy. Using projection methods like fluoroscopy and x-ray projections in conventional small bowel enteroclysis several bowel loops are superimposed.

MRI as well as CT imaging acquires sectional image data. Even for a trained radiologist it is difficult to follow the bowel continuously by slicing through all the axial images forward and back and keeping track of the tortuous bowel loops.

Recently introduced advanced graphics computer workstations and software allow volume rendered 3D reconstruction of sectional data in real time.

There are different approaches to visualize sectional 2D data as a 3D model. Basically the surface rendering and volume rendering methods have to be distinguished\textsuperscript{31}. For surface rendering the desired structure has to be outlined on every source image. This method is time consuming prone to individual error. Additionally only 10\% of the acquired information is used for reconstruction\textsuperscript{32}.

Using volume rendering\textsuperscript{33,34} basically no major manual image processing is necessary. Using certain default values a particular color, opacity and reflection is assigned to each voxel in the volume data set depending on its signal intensity. The data is rendered as a 3D model immediately and the entire volume data set is employed for reconstruction. The reconstruction method is barely user dependent. Next to the 3D models a virtual endoscopic view can be created easily. The software simulates endoscopic equipment by representing default values for size and optical properties of existent endoscopes from different major vendors.

The feasibility of virtual endoscopy of the small bowel is just mentioned in one phantom study\textsuperscript{35}. This group tried to optimize spiral CT protocols for depiction of small bowel phantom lesions.

Comprehensive 3D models which integrate the information from hundreds of single slices in one all-embracing model can help to cope the workload of 2D reading. Still the primary diagnosis is done by meticulous reading of the 2D images in MR imaging. With some exceptions there is no additional diagnostic benefit in 3D imaging alone. However,
the volume rendering technique, which barely needs any time consuming post processing, represents a good addition without major efforts.

We conclude, that high resolution MR based virtual endoscopy is feasible in most cases. The virtual endoscopy of the small bowel reveals interesting inside views, which can hardly be completely acquired by optical endoscopy. Although the quality of most virtual flights was not considered adequate to real optical endoscopy our approach should be a first step in comprehensive small bowel visualization. With increasing time and volume resolution in MRI this could lead to new diagnostic modalities with endoscopy like intraluminal views of the small intestine.

Applying the easy and fast to perform volume rendering algorithms the addition of 3D imaging and virtual endoscopy could be added to small bowel routine examinations in a clinical environment. Further studies are needed to address specific problems found such as bowel motion or inadequate intestine filling as well as clinical applications for this technique. Finally the clinical value has to be tested in larger trials using outcome criteria.
### Table 1: Visualization quality of small bowel virtual endoscopy

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<tr>
<th>Quality of the small bowel virtual endoscopy</th>
<th>Visualized Pathology</th>
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<tr>
<td>Total n=30</td>
<td>Fistula n=3</td>
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<tr>
<td>Poor 3</td>
<td>Stenosis terminal ileum n=3</td>
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<tr>
<td>Fair 18</td>
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<td>Good 9</td>
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*Table 1: The overall quality of small bowel virtual endoscopy was subjectively assessed: 27/30 (90%) were considered fair to good, 3/30 (10%) had poor quality because of motion or filling artifacts. All pathological changes like fistula or stenosis were visualized with fair to good quality.*
References:

Figures:

**Figure 1:** User interface of the virtual endoscopy software: In the left main window the volume rendered 3D reconstruction based on small bowel MRI is depicted. The right upper window shows the corresponding 2D image. The lower window on the right depicts the virtual endoscopic view.

**Figure 2:** Volume rendered 3D reconstruction of the stomach and small bowel based on MR imaging. The external view can be watched interactively from any direction.
**Figure 3:** Left window external view on the small bowel. The virtual camera is positioned in the proximal jejunum. Right upper window corresponding coronal MRI. Right lower window virtual flight through the jejunum.

**Figure 4:** Fistula in the ileum (A) depicted with virtual endoscopic view (green point). The virtual camera approaches (B) and enters (C) the fistula.
Figure 5: The volume rendered external view illustrates a stenosis of the terminal ileum (A). The green arrow represents the position of the virtual camera targeting from the terminal ileum towards the cecum resulting in a virtual endoscopic view of the stenosis (B).