MEDINFO 2001
V. Patel et al. (Eds)
Amsterdam: IOS Press


# A Review of Technical Advances in Virtual Colonoscopy

**Frans Vos[a,c], Iwo Serlie[a,b], Rogier van Gelder[d], J. Stoker[d], Henri Vrooman[c], Frits Post[b]**

[a]*Pattern Recognition Group, Delft University of Technology, Delft, The Netherlands*
[b]*Computer Graphics & CAD/CAM Group, Delft University of Technology, Delft, The Netherlands*
[c]*Biomedical Imaging Group Rotterdam, Erasmus University Rotterdam, Rotterdam, The Netherlands*
[d]*Department of Radiology, Academic Medical Center, Amsterdam, The Netherlands*

**Abstract**

*Early detection of polyps has proven to lead to a decrease in incidence of colon cancer. In the past few years, virtual colonoscopy has been developed as a patient-friendly screening technique. The procedure comprises the following steps. First, the patient's colon is cleansed and transanally inflated with air. Subsequently, a 3D image volume is acquired of the abdomen by CT or MRI. Finally, the bowel surface is extracted and visualized, after which the physician virtually navigates through the colon and examines the surface for abnormalities. This paper describes the progress in research for virtual colonoscopy.*

***Keywords:***

Medical Informatics; Image Processing; Scientific Visualization; Virtual Endoscopy.

## Introduction

Colorectal malignancies are among the leading causes of cancer deaths in the Western world [1]. Early detection of polyps has proven to lead to a decrease in incidence [2]. To enable large-scale screening, an effective procedure to detect such polyps is needed.

Until recently, barium enema and optical colonoscopy were the two procedures available for examining the colon [3][4]. In the 'double contrast barium enema', several planar X-ray images are acquired of the abdomen by rotating the camera around the patient. Immediately before image acquisition a barium solution followed air is injected into the bowel via the anus. The radio-opaque barium sticking to the colon wall enables the visualization of the surface as a white structure on a dark background. In conventional colonoscopy an endoscopic camera is transanally guided through the colon. By manipulating the tip of the probe, the physician inspects the inner surface for abnormalities. A drawback of the barium enema is the radiation burden. Moreover, the sensitivity is rather poor (50-80%, for polyps smaller than 1 cm in diameter [3]). Colonoscopy requires intravenous sedation, while the colon ascendens often cannot be accessed by the endoscope [4]. The sensitivity is estimated to be in the order of 80-82% for small polyps.

People eligible for screening often avoid the examinations, because of the associated discomfort [5]. In the past few years, virtual colonoscopy (VC) has been developed as a patient-friendly alternative [6]. First, the patient's colon is cleansed and transanally inflated with air. Subsequently, a 3D image volume is acquired of the abdomen by CT or MRI. Finally, the interior bowel surface is extracted and visualized, after which the physician virtually navigates through the colon and examines the surface for abnormalities (Figure 1).

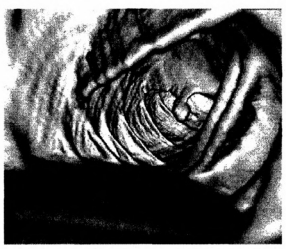

*Figure 1 – Virtual endoscopic view of a protruding polyp*

Radiologists have immediately recognized the importance of this new technology. Currently, VC is already clinically used in a few institutions [8]. Progress in medical informatics has made a considerable contribution to its success [7]. For general application, however, further improvements are required on patient friendliness, cost effectiveness, sensitivity for polyps and radiation dose (if any).

## State-of-the-art methods

The virtual endoscopic examination can be modeled to comprise four stages: *patient preparation*, *image acquisition*, *visualization* and *diagnostic examination*. In the next sections we will review techniques related to each step.

### Patient preparation

For optimal visualization, proper patient preparation is required prior to scanning. Conventionally, the procedure consists of the following steps [8][9][10]:

- On the day before the examination, the patient is asked to drink 4-5 liter of a laxative fluid (e.g. X-prep, Golytely, Dulcolax or CleanPrep [10]). Such a regime is necessary

since remaining faeces may easily be interpreted as polyps [11][12].

- Immediately before data acquisition, a bowel relaxant may be administered intravenously. Although the beneficial effect has been disputed [13], many investigators use Glucagon or Buscopan (1mg) to prevent movement artifacts due to peristalsis [10].
- For distension and to introduce contrast, different agents have been proposed. In CT colonoscopy 1.5-2.0 liter carbon dioxide or room air is transanally brought in the colon[14]. Fluid gadolinium solutions (e.g. 20 mM/l) are applied in magnetic resonance imaging [15].

A persisting problem at this stage is remaining stool. Fecal rests cause false positive findings and fluid rests occlude parts of the colon wall (notice the fluid surface in Figure 1 at the bottom).

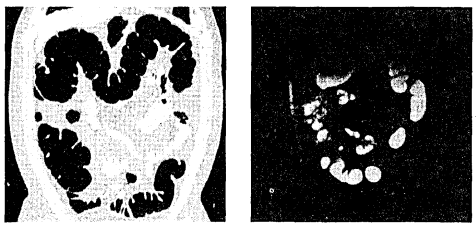

*Figure 2 – Images acuired with CT (left) and MRI (right)*

**Data acquisition**

Advances in image acquisition technology (MRI and CT, see Figure 2) have given a strong impetus to virtual endoscopy. In CT imaging, the development of spiral multi-detector scanners enabled acquisition within a breathhold at a high resolution [16]. Thus, movement artifacts are largely prevented and partial volume effects are reduced [11].

*Table 1 – Typical scan parameters with CT colonoscopy*

| Acquisition parameter | Low-dose protocol | High-resolution protocol |
|---|---|---|
| Tube current | 50-100 mA | 120 mA |
| Collimation | 2.5-5.0 mm | 1.0-1.5 mm |
| Table feed/rotation | 12.5-15.0 mm | 6.0-7.5 mm |
| Rotation time | 0.5-0.8 s | 0.5-0.8 s |
| Rec. increment | 1.5-3.0 mm | 0.8 mm |

Sample scanning parameters for CT colonoscopy are given in Table 1 [10]. A typical low dose protocol yields 200-300 images of $512^2$ pixels at a resolution of about $0.75^2$ x 3 $mm^3$. The amount of images with a high resolution protocol can be 450-500 slices of 0.8 mm thickness.

MR colonoscopy has come within reach with the development of increasingly faster gradients. Two common scanning protocols apply a 3D gradient echo or a Haste sequence [9][17]. Typical scan parameters are given in Table 2 [10].

Factors influencing contrast are the flip angle (3D GRE) and the echo time (Haste sequence). In a 3D GRE sequence the highest possible flip angle is chosen to optimize positive contrast (bright colon on a dark background). To maximize the negative contrast in a Haste sequence an echo time between 60 and 80 sec. is selected.

*Table 2 – Typical scan parameters with MR colonoscopy*

| Acquisition parameter | 3D GRE | Haste |
|---|---|---|
| $T_r$, $T_e$, Flip angle | min, min, max | -, 60-80, 90° |
| Slice thickness | 1.2-6.0 mm | 8 mm |
| Matrix | 256x160 | 256x160 |
| Field of view | 36-44 cm | 36-44 cm |

Both prone and supine scanning remains essential both with CT and MRI to enhance distension and resolve possible ambiguities due to stool rests [18]. Clearly, such an approach goes at the expense of a doubled radiation dose with CT. On the other hand, sub-optimal contrast and resolution still obstructs large-scale application of MRI [10].

**Visualization**

For visualization of CT or MRI volume data, there are two techniques available: surface fitting and direct volume rendering [19]. Surface fitting is a preprocessing step to extract iso-valued surfaces from the data volume. The 'marching cubes' algorithm [20] is often used to this end, resulting in an approximation by large triangle meshes. Conventionally, 3D graphics hardware can be used for fast visualization. The number of generated polygons, however, grows exponentially with the volume size. For high resolution data, this number is typically between $10^5$ and $10^6$ triangles. Thus, interactive viewing is only possible using powerful graphics accelerators, or after a reduction of the mesh size [21] (which is at the expense of loss in accuracy and fine details [22]).

Information on the local signal values is lost in surface extraction. Direct volume rendering (DVR) preserves such information by projecting an image of the 3D data volume on the screen [23][24]. An example of DVR is volume ray casting (Figure 3). The image is generated by casting a ray from the viewpoint through each pixel on the screen into the data volume. Next, the volume is sampled along the ray. A transfer function associates the data values with values for color (RGB) and opacity (0-1). The color of each image pixel is determined by 'compositing' the color and opacity values in front-to-back order along the ray.

Both surface fitting and DVR have been successfully applied in virtual colonoscopy.

**Diagnostic examination**

Currently, most implementations of surface and volume rendering do not allow interactive visualization. To meet the real-time constraint, image sequences are generated off-line for later diagnostic examination by the physician. Viewing positions are taken on a central path through the colon's lu-

men. Several strategies were proposed in the literature [26][27] to automatically obtain the path, such as skeletonization of the segmented colon's interior volume. Typically, image sequences are generated, that show views from coecum to rectum and vice versa. Thus, the amount of displayed surface is maximized. Such an approach still yields selective views on the colon wall: important surface parts may be missed, while insignificant parts are considered twice.

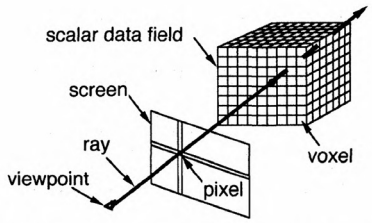


*Figure 3 – The principle of volume ray casting*

To solve the latter inefficiency, so-called panoramic views are currently explored. One approach implies folding out the colon, and spreading the inner wall on a flat plane, so that the full surface is exposed for examination. Several techniques are described in the literature, from simple cylindrical coordinate transforms, to complex conformal mappings [28][29]. The cylindrical transform produces excessive distortions, while local geometry is much better preserved in a conformal mapping. As an alternative, we have worked on an 'unfolded cubic' rendering (see Figure 4) [30]. Thus, a full 360 degree view is allowed from a given point.

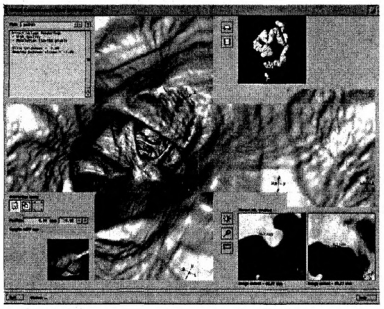

*Figure 4 – Our unfolded cube representation*

Any visualization technique relies heavily on a proper representation of the geometric information. Important cues such as vascularization texture are unavailable. For optimal exploitation of surface geometry, some methods for automatic detection of polyps have been suggested. Common techniques are based on local principal curvatures, circle fitting and analysis of surface normal orientation [31][32]. Though currently rather crude, automatic polyp detection may well serve as a visual support for inspection.

## Ongoing research

This section describes ongoing work specifically in relation to requirements such as patient comfort, cost effectiveness, sensitivity and radiation dose.

**Patient preparation**

Previously, remaining stool was identified as an important impediment for practical purposes. To reduce such artifacts, optimal cleansing is essential. The patient friendliness, however, is enhanced if a less intensive cleansing regime could be performed. In CT colonoscopy both requirements may be met by way of a radio-opaque substance (e.g. iodine) added to the laxative fluid [33]. Consequently, labeled stool can be identified by a high signal density [12]. Unfortunately, contradictory results regarding sensitivity are reported [34].

Stool is more mobile with the liquid contrast agent in MR colonoscopy [35]. For that reason, imaging in prone and supine position in itself is usually sufficient to distinguish fecal material. A change in position of the patient is also required in MRI to redistribute air so that obscured parts of the colon surface may become visible. Any remaining ambiguities caused by faeces may be prevented by oral ingestion of gadolinium in combination with a stool softener [35]. As a result, fecal rests get the same characteristics as the surrounding gadolinium solution.

Information about the perfusion can be obtained by intravenous contrast injection both in CT and MR colonoscopy. Iodinated contrast (1.6 g iodine/s) significantly improves polyp detection with CT [36]. Connected to MR gadolinium and blood pool agents promise to fulfil this aim [10]. In due time such methods may facilitate indirect visualization of the mucosal color and digital cleansing.

**Data acquisition**

The obvious drawback of CT is the use of ionizing radiation. Not surprisingly, several authors describe efforts to minimize the radiation exposure (without jeopardizing the sensitivity) [37][38]. At 70 mA, scanning in supine *and* prone position corresponds to a radiation dose for a barium enema. It has been demonstrated that lowering the exposure to 50 mA does not affect the sensitivity [38]. The benefits of MRI in this respect are obvious. Another advantage is MRI's enormous potential for visualizing contrast in soft tissue (structures behind the colon wall). Regrettably, CT image resolution and contrast between colon wall and interior are superior [10]. Also, the cost for contrast material and equipment for MRI is higher. Current MR slice thickness (specifically in a Haste sequence) is too large for the detection of smaller polyps. Moreover, signal inhomogeneities, due to receiver bias and gadolinium suspension, complicate visualization. As yet, CT will remain state of the art, although further development of MR colonoscopy is justified.

**Visualization**

Surface rendering (SF) is often applied in VC under the assumption that the signal change between wall and lumen is instantaneous. To avoid decimation, only those polygons may be submitted to the rendering pipeline that are visible from the viewing frustrum [6]. Information about the detailed structure of the mucosa, however, is omitted [22].

In [22] it is demonstrated how the mucosal interface can be better visualized by direct volume rendering (DVR). Moreover, exploration of the tissue beneath the surface is supported

by a sophisticated adaptation of the transfer function. The latter aspect may help in differentiating benign tissue from malignancies.

Currently, interactive frame rates in DVR are only available for moderately-sized data volumes on high-end graphics workstations, by using special-purpose hardware [25] or rendering algorithms [22]. Perspective projection is required for a good view of the colon interior, but is not always supported by efficient DVR algorithms or hardware. The situation in visualization speed is changing rapidly, and real-time surface and volume rendering will soon be available on common PC platforms. With SF as well as with DVR, real-time interaction is not yet generally available. This hindrance, however, is solved merely by generating a sequence of images offline.

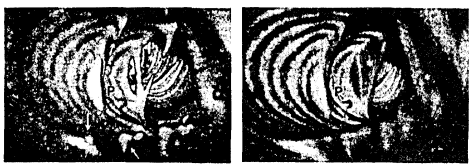

*Figure 5 – Stair-step and shine-through artifacts. Left and right images were created with different transfer functions*

**Diagnostic examination**

An obvious drawback of reviewing the data by means of a sequence of images is the limited surface in view. For a unidirectional movie (from coecum to rectum), as much as 25% of the colon may be missed [30]. Bi-directional sequences reduce this number to 7%. Only when lateral as well as top and bottom renderings are added, comes the full surface in view. Our unfolded cubic renderings tries to achieve this result (Figure 4) [30].

Typical artifacts during exploration are caused by improper cleansing, incorrect segmentation and sub-optimal resolution [11]. Precautions against incomplete cleaning were discussed earlier. Figure 5 shows the characteristic stair-step and shine-through artifacts, caused by severe anisotropy in the slice direction respectively improper opacity setting. The stair-step artifact just hinders the visualization and can only be avoided by using thinner slices. Physicians must be specifically aware of the shine-through artifact as it may easily result in false positive and false negative findings. These misinterpretations can be avoided to some extent by adapting the transfer function at each time a suspicious area is encountered.

The effectiveness of CT colonoscopy has been extensively studied in the literature ([10] shows a nice summary). In one of the latest reviews [39] the sensitivity for polyps larger than 10 mm approximates 100%. For polyps from 5-10 mm this comes to 61-80% (there is no data on smaller polyps). Not much literature is available regarding MRI. In [17], MRC sensitivity for polyps larger than 10 mm is found to be 96%. For polyps between 6-10 mm it is 61%, while smaller masses remain undetected. The poor performance of both techniques with smaller polyps is not considered very important. Nearly all of them are benign, while their identification may increase the number of unnecessary operations [10]. The strong correlation between polyp size and the risk of malignant transformation justifies a minimum polyp size of 5 mm.

## Conclusions

VC is becoming a state-of-the art screening tool for colorectal polyps. In a few years time, a standardized protocol has emerged. Progress in medical informatics had an important contribution to its development. Modern image processing and visualization techniques enabled modeling and rendering of inner views on the colon wall. Further improvements, however, are needed.

The cleansing regime may be less strict to enhance patient acceptance. In addition, tools should be devised to cope with faeces. Any such technique should facilitate a low number of false positives and unobstructed views on the surface (no occlusion by remaining fluid). MR colonoscopy can be improved regarding resolution (slice thickness) and signal homogeneity. Alternatively, CT radiation dose has to be reduced to its minimum. The poor interactivity during exploration requires enhancement, so that in real time inspection is possible. At last, techniques are needed to review the *full* colon surface at once.

The research described in this paper indicates that important steps are made in the right direction. It is expected that VC will become a standardized tool for radiologists.

## References

[1] Potter JD, Slattery ML, Bostick RM. Colon cancer: a review of the epidemiology. *Epidemiol Rev* 1993: 15 pp. 499-545.

[2] Toribrara NW, Sleisenger MH. Screening for colorectal cancer. *N Engl J Med* 1995: 332 pp. 861-867.

[3] Dodd GD. Colon cancer and polyps imaging perspectives. *Proc First International Symposium on Virtual Colonoscopy,* Boston University Press, 1998: pp. 15-17.

[4] Rex DK, Cutler CS, Lemmel GT. Colonoscopy misrates of adenomas determined by back-to-back colonoscopies. *Gastroenterology* 1997: 112 pp. 24-28.

[5] Winawer SJ, Fletcher RH, Miller L. Colorectal cancer screening: clinical guidelines and rationale. *Gastroenterology* 1997: 112 pp. 594-642.

[6] Hong L, Muraki S, Kaufman A, He T. Virtual voyage: interactive navigation in the human colon. *Proc ACM SIGGRAPH Conf.* ACM Press, 1997; pp. 27-34.

[7] Lorensen WE, Jolesz FA, Kikinis R. The exploration of cross-sectional data with a virtual endoscope. *Interact Techn and the New Health Parad* 1995: 459 pp. 221-230.

[8] Helen M, Ferucci JT. Virtual endoscopy becomes viable option. *Gastroenterology* 1999: 114 pp. 57-68.

[9] Luboldt W, Bauerfeind P, Steiner P, Fried M, Krestin GP, Debatin JF. Preliminary assessment of three dimensional magnetic resonance imaging for various colonic disorders. *Lancet* 1999: 349 pp. 1288-1291.

[10] Fletcher JG, Luboldt W. CT colonography and MR

colonography: current status, research directions and comparison. *Eur Radiol* 2000: 10 pp. 786-801.

[11] Fenlon HM. Image Artefacts on virtual colonoscopy. *Proc Second International Symposium On Virtual Colonoscopy*. Boston University Press, 1998; pp. 40-41.

[12] Lakare S, Wan M, Sato M, Kaufman A. 3D Digital Cleansing Using Segmentation Rays. *Proc IEEE Visualization Conf.* ACM Press, 2000; pp. 37-44.

[13] Yee J, Hung RK, Akerkar GA, Wall SD. The usefulness of glucagon hydrochloride for colonic distention in CT colonography. *Am J Roentgenol* 1999: 173. pp. 169-172.

[14] Rogalla P, Schmidt E, Korves M, Hamm BK. Optimal colon distention for virtual colonoscopy: room air versus $CO_2$ insufflation. *Radiology* 1999: 213 p. 342.

[15] Luboldt W, Bauerfeind W, Wildermuth S, Debatin JF. Contrast optimization for assessment of the colonic wall and lumen in MR colonography. *J Magn Reson Imaging* 1999: 9 pp. 745-750.

[16] Halligan S, Fenlon HM. Science, medicine, and future - virtual colonoscopy. *Brit Med J* 1999: 319 pp. 1249-1252.

[17] Luboldt W, Steiner P, Bauerfeind P, Pelkonen P, Debatin JF. Detection of mass lesions with MR colonography. *Radiology* 1998: 207 pp. 59-65.

[18] Chen SC, Lu DSK, Hecht JR, Kadell BM. CT colonography: value of scanning in both the supine and prone positions. *Am J Roentgenol* 1999: 172 pp. 595-599.

[19] Shahidi R. Surface rendering versus volume rendering in medical imaging: techniques and applications. *Proc IEEE Visualization Conf.* ACM Press, 1996; pp. 439-440.

[20] Lorensen WE, Cline HE. Marching cubes: a high resolution 3D surface construction algorithm. *Proc ACM SIGGRAPH Conf.* ACM Press, 1987; pp. 163-169.

[21] Garland M, Heckbert PS. Surface simplification using quadratic error metrics. *Proc ACM SIGGRAPH Conf.* ACM Press, 1997; pp. 209-216.

[22] Hopper KD, Lyriboz AT, Kasales CJ. Mucosal detail at CT virtual reality: surface versus volume rendering. *Radiology* 2000: 214 pp. 517-522.

[23] Levoy M. Display of surface from volume data. *IEEE Comp Graph and Appl* 1988: 8 pp. 29-37.

[24] Kaufman A. *Volume Visualization.* Los Alamitos (CA): IEEE Computer Society Press, 1991.

[25] Pfister H, Hardenbergh J, Seiler L. The VolumePro real-time ray casting system. *Proc SIGGRAPH Conf.* ACM Press, 1999; pp. 251-260.

[26] Paik D, Beaulieu CF, Jeffrey RB, Rubin GD, Napel S. Automatic flight path planning for virtual endoscopy. *Med Phys* 1998: 25 pp. 629-637.

[27] Bitter I, Sato M, Bender M. CEASAR: A smooth, accurate and robust centerline extraction algorithm. *Proc IEEE Visualization Conf.* ACM Press, 2000; pp. 45-52.

[28] Beaulieu CF, Jeffrey RB, Napel S. Display model for CT colonography: Part II. *Radiology* 1999: 212 pp. 203-212.

[29] Haker S, Angenent S, Tannenbaum A, Kikinis R. Non distorting flattening for virtual colonoscopy. *Proc MICCAI conf.* Springer, 2000: pp. 358-366.

[30] Serlie IWO, Vos FM, Post FH. Cubic rendering in virtual endoscopy. Submitted for publication to *EG/ IEEE VisSym Conf* 2001.

[31] Beaulieu CF. Computer aided detection of colonic polyps. *Second International Symposium on Virtual Colonoscopy*. Boston University Press, 2000; pp. 73-77.

[32] Summers RM, Beaulieu CF, Napel S. Automatic polyp detector for CT colonography: feasibility study. *Radiology* 2000: 216 pp. 284-290.

[33] Wax MR. Virtual colonoscopy - CT contrast agents. *Second International Symposium on Virtual Colonoscopy*. Boston University Press, 1998; pp. 66-68.

[34] Pineau BC, Vining DJ. Ability of virtual colonoscopy to detect patients with colorectal polyps. *Gastroenterology* 1999: 116 (Suppl A485).

[35] Weisenhaupt D, Patak MA, Froehlich J, Ruehm S, Debatin JF. Feacal tagging to avoid colonic cleansing before MRI colonography. *Lancet* 1999: 354, pp. 835-836.

[36] Morin MM, Kruskal JB, Farell RJ, Reynolds KF, Raptopoulos VD. Intravenous contrast material enhances the diagnostic accuracy of CT colonography. *Radiology* 1999: 213 (Suppl. 257).

[37] Brink JA. Radiation dose: impact of multi-slice CT. *Second International Symposium on Virtual Colonoscopy*. Boston University Press, 1998; pp. 27-29.

[38] Gelder RE van, Stoker J, Lameris JS. Radiation dose reduction for 3D-CT colonography. *Second International Symposium on Virtual Colonoscopy*. Boston University Press, 2000; p. 96.

[39] Johnson CD, Dachman CD. CT colonography: the next colon screening examination? *Radiology* 2000: 216 pp. 331-341.

[40] McFarland EG. Clinical experience of polyp detection. *Second International Symposium on Virtual Colonoscopy*. Boston University Press, 1998; pp. 19-20.

[41] Hietala R, Oikarinen J. A Visibility Determination Algorithm for Interactive Virtual Endoscopy. *Proc. IEEE Visualization Conf.* ACM Press, 2000; pp. 29-36.

**Address for correspondence**

F.M. Vos, Lorentzweg 1, 2628 CJ Delft, The Netherlands
E: frans@ph.tn.tudelft.nl; Phone.: +31 15 278 3221, Fax: +31 278 6740.