Creating real-time volume-rendered endoscopic views while the physician is navigating through the 3D virtual colon.

VIRTUAL COLONOSCOPY

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A computer-graphics-based alternative to conventional optical colonoscopy, known as virtual colonoscopy (VC) or computed tomography colonography (CTC), is rapidly gaining popularity. During this procedure, which was concurrently developed by our group at Stony Brook University [5] and by other researchers [10], the distended colon is imaged by a helical or multislice CT scanner. The acquired abdominal CT scan commonly consists of 350–750 axial images of 512x512 sub-millimeter resolution, providing excellent contrast between the colon wall and the lumen. A 3D model of the colon is then reconstructed from the CT scan by automatically segmenting the colon out of the rest of the abdomen and employing an electronic cleansing algorithm for computer-based removal of the residual

material. The PC-based visualization software employs volume rendering and allows the user, typically a physician, to interactively navigate through the virtual 3D model of the colon. An intuitive user interface with customized tools supports measurements and virtual biopsy to inspect suspicious regions. Unlike optical colonoscopy (see the sidebar "Conventional Colorectal Cancer Screening"), VC is patient friendly since the patient undergoes less rigorous preparation prior to the procedure. VC is also a fast, noninvasive, highly accurate, cost-effective method for mass screening of colon polyps.

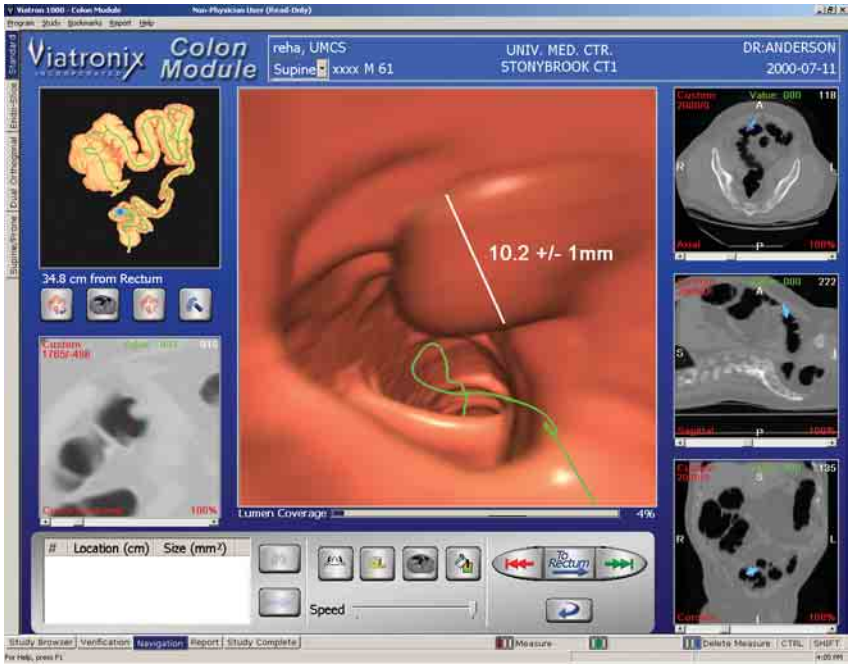

Figure 1. A user interface for the virtual colonoscopy system (courtesy of Viatronix, Inc.).

Data Modeling

An effective colonoscopy is only possible if there are no residual materials in the colon that could be falsely interpreted as polyps. Most current approaches, either optical or virtual, involve complete physical bowel cleansing. Our approach is by far the preferred procedure by patients as it replaces the physical cleansing with virtual cleansing of the CT scan data. This process, called electronic cleansing, relies on oral contrast agents containing barium and/or iodine to increase the density of the residual material in the CT scan, which is then automatically identified through a combination of thresholding and neighborhood feature analysis [6]. However, just setting the identified high-intensity voxels to zero would transition to the surrounding tissue voxels with a discontinuous intensity jump. The transition voxels initially contain the partial volume averaging of low-density, low-intensity, soft tissue and high-intensity tagged material, where in a physically cleansed colon they would contain lower values due

CONVENTIONAL COLORECTAL CANCER SCREENING

Colorectal cancer currently ranks as the third most common human malignancy and the second leading cause of cancer-related deaths in the U.S. The overall risk of developing the disease is approximately 5% over a lifetime. There are approximately 130,000 new cases of colorectal cancer and 60,000 deaths each year in the U.S. Most colon cancer cases arise from adenomatous polyps, which can take five to 15 years for malignant transformation. The risk of developing carcinoma from a polyp is directly related to its size: essentially 0% risk if the polyp is less than 5mm, 1% risk if size is 5mm—10mm, 10% risk with size 10mm—20mm, and at least 30% risk with polyps larger than 20mm. Survival rates from colon cancer are related directly to the pathologic staging of the disease, and are over 90% when cancers are limited to the bowel wall. Whereas 75% of cancers found by screening in asymptomatic patients are confined to the bowel wall, more than half of those with symptoms had a more advanced stage.

The American Cancer Society recommends that screening begin at age 50 for asymptomatic, average-risk patients. Conventional optical colonoscopy employs a long fiber-optic medical instrument, called an endoscope, which can also biopsy and/or remove detected polyps, and is generally considered the "gold standard," although miss-rates of 18% of adenomas larger than 6mm have been reported on consecutive optical colonoscopies. It is also expensive, uncomfortable, requiring harsh colon cleansing and sedation, time-consuming, and invasive, with a risk of perforation (one in 500—1,000 cases) and death (one in 2,000—5,000 cases). It also fails to examine the entire colon in approximately 10% of patients, and is ineffective in examining blocked areas of the colon or in areas of extreme narrowing. C

to the partial volume averaging of soft tissue and air. Hence, we not only remove high-intensity voxels, but also properly reconstruct the surrounding tissue by inversion of the density profile. This transition region reconstruction allows us to render images of the reconstructed colon wall in high quality. In addition, we completely remove the partial volume effect voxels between the tagged material and air by using segmentation rays, which are special rays sent from the tagged material that allow us to detect the partial volume voxels [6].

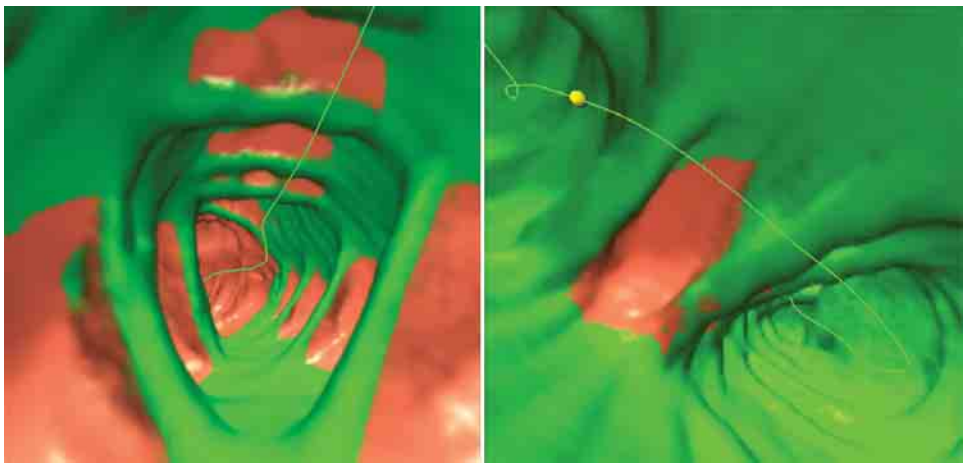

Figure 2. Endoscopic view of painted information after an antegrade flythrough (left); and an example of a missed patch after both antegrade and retrograde flythroughs (right). The green areas were visualized, while the reddish areas were missed.

On many VC systems the CT data is presented in its raw form and the radiologist must manually browse through hundreds of 2D axial images of the colon in a search for abnormalities. Our system instead preprocesses the CT data automatically into multiple layers of metadata to make the subsequent data analysis in 3D as convenient and natural as possible. First, it segments the colon lumen from the CT volume. This process includes finding multiple colon segments that may be separated due to large masses or a colon collapse as well as automatic connection of these segments in the most likely order. Our system then computes the potential fields used for guiding the navigation and for collision avoidance during interactive navigation inside the colon [5].

For guiding an automatic or interactive navigation along a flight path we use the colon centerline, and we have developed a fast and degeneracy-free method to compute the centerline [2]. In this approach, we use the direction of gradients in a small neighborhood to find local distance minima and maxima, which are good candidates for voxels on or close to the centerline. We connect the local minima to the local maxima along a path of potential centerline voxels. The next step is to automatically find one of the centerline endpoints. We do this through accumulation of the piecewise Euclidian distance from one arbitrary potential centerline voxel to all other potential centerline voxels. In order to avoid a centerline that would scrape along the colon wall, we add a penalty to the Euclidian distance calculation at each potential centerline voxel. This penalty is high at the colon boundary and low in the colon center. A Dijkstra shortest path algorithm computes incrementally the accumulation of the Euclidian distance as well as the penalty. The voxel with the largest accumulation must be at the very extreme of the colon and is one of the two endpoints. The furthest voxel from the first endpoint gives the other centerline endpoint. Backtracking to the source voxel in this field yields the desired well-centered discrete centerline. A last step of constraint smoothing creates a smooth continuous centerline that we use as the flight path for navigation. This centerline is displayed in green in the endoscopic view at the center of Figure 1 and in the outside overview of the colon in the upper-left corner.

Data Analysis

Traditionally, radiologists interpreted CT scans by viewing the separate hard-copy film images in a 2D matrix against an illuminated box mounted on a wall. More recently, the 2D images were viewed on a computer by sequencing the images on the computer display. Only very recently have 3D reconstructed images begun to be used to view the CT data. Researchers have shown that if all surfaces of the colon lumen have been seen, 3D endoscopic navigation has a higher sensitivity of polyp detection than viewing only 2D axial images [1, 9].

The interactive interface shown in Figure 1 provides multiple views of the patient data. The 2D mutually perpendicular slice views oriented axial, sagittal, and coronal are shown down the right side. An oblique reformatted slice perpendicular to the colon centerline is shown in the middle-left side. The upper-left corner shows an outside overview map of the patient's colon with indication of current virtual position and orientation, possible bookmarks of suspicious regions, and with the centerline shown in

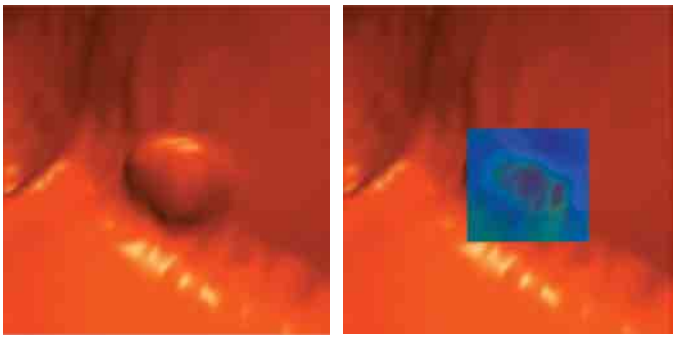

Figure 3. A volume-rendered surface view (left) and an electronic biopsy (right) of a polyp.

green. In the center is the 3D volume rendered endoscopic view using standard perspective projection, with a green centerline. A 10.2mm polyp is clearly seen in this view, along with its measurement. All of these 2D and 3D images are correlated and interlinked so that position in 3D is overlaid on the 2D images and positions of 2D slices can be overlaid on the 3D images. This provides a quick and simple mechanism to easily analyze suspicious areas in both 2D and 3D.

One of the primary advantages of VC over optical colonoscopy is the ability to interactively and freely pan and zoom the virtual camera for close examinations, and further turn it around (in essence 180 degrees) to view behind folds and sharp bends. This allows viewing a much larger percentage of the colon lumen surface compared to optical colonoscopy. In our system, we keep track of which surfaces on the colon wall have been previously displayed. In fact, simulated optical colonoscopy (a flight in one direction through the colon) viewed an average of 74% of the colon surface, primarily missing the backsides of haustral folds and around sharp bends. VC, with noninteractive flythroughs along the centerline, both forward (antegrade) and backward (retrograde), viewed an average of 89% of the surface. With interactive navigation, VC can achieve 100% coverage [11].

For each rendered image, any voxel that contributes sufficiently to a pixel of the image is marked as visualized. We also paint all previously visualized wall voxels with a unique green color in a special volume rendering display of visualized versus not-yet-visualized surfaces; example images are shown in Figure 2. An automated visualized area detection system is used in our system. Once the user has flown along the centerline in both directions, the visualized-marking information is processed and a list of missed patches is created. The patches are sorted by size (voxel count) and displayed in a list-box (at the bottom-right corner of Figure 1) allowing the physician to step though the list to view each patch. After stepping through the missed patches, the viewer can simply and efficiently achieve 100% coverage of the colon lumen [11].

Real-Time Volume Rendering

Volume rendering is the process of creating a 2D image directly from the 3D volumetric dataset of voxels. Although direct volume rendering methods may depict surfaces contained within the volumetric data, they nevertheless operate directly on the actual volumetric data samples, without intermediate geometric surface approximation. Volume rendering can be achieved using object-order (splatting), image-order (ray casting), object-image hybrid order (shear-warp), or domain-based (compression) techniques. Ray casting, in which a ray is cast from every pixel in the image plane through the volumetric data to determine by integration the value of the pixel, is the most accurate and most common technique, especially in medical applications.

Previously, volume rendering was an extremely expensive technique to provide frame rates fast enough to allow interactive navigation. For this reason, many early VC systems used a surface-rendering approach for which hardware acceleration was available. It is generally accepted that volume rendering provides a much more accurate representation of the true surface of the colon lumen since it does not force piecewise planar approximation to the surface creating artifacts that are not present in the data while, at the same time, removing small details.

Recently, interactive volume rendering has become available on PC-class machines as well as true real-time rendering using the VolumePro [8] hardware acceleration card, which is based on our Cube-4 architecture [7]. The VolumePro card provides 30 frames per second only in parallel projection, not perspective projection as required for virtual endoscopy applications. We have thus developed a method to provide high-quality images at interactive rates for perspective projections using a multipass approach with the VolumePro rendering card. Now that volume rendering is available from either highly optimized PC solutions or hardware acceleration add-ons, it is much preferred compared to the lower accuracy surface-rendering approach C

Rendering

A primary significant technological advance of our work is that the 3D volume rendered endoscopic views are created "live" while the user is interacting with the system. This has two important consequences. First, the user does not have to wait for a motion video to be generated, which often requires 15–30 minutes. Secondly, the user is able to auto-fly along the centerline to get a good view of most of the colon surface, but also interactively fly off the centerline similar to computer game navigation. This allows the user to get a better view of suspicious structures, examining and analyzing them from any angle. An important performance measure for interactive navigation is frame rate. Our system relies on years of volume rendering research conducted at Stony Brook University to achieve at least 15 rendered frames per second [7, 11]. At this rate the interactive response is perceived as natural and smooth. Previous systems only achieved between several seconds per frame to a few frames per second, which resulted in cumbersome interactivity that most users ceased using.

Because we employ volume rendering (see the sidebar "Real-Time Volume Rendering), we are not limited to a surface view of the colon lumen. We provide a translucency view, called electronic biopsy, shown in Figure 3. When the user is navigating and viewing the colon wall as an opaque surface, only shape can be analyzed. In essence, the user is viewing the geometry of the colon surface and can make analysis such as "here is a bump in the wall." The electronic biopsy permits the user to see behind the colon wall and analyze the inner structure of suspected abnormalities. In this way the user can evaluate not just shape, but also texture, or density makeup, of an abnormality to confirm the abnormality is indeed a polyp and thus reducing the number of false positives.

Clinical Outlook

Since inception of VC approximately a decade ago, more than 20 clinical trials, including one at Stony Brook University Hospital involving a total of several thousand patients, have been published in the medical literature. The performance has been very encouraging, with sensitivity (percentage of true polyps that were found with VC) and specificity (percentage of cases where a polyp was detected that doesn't actually exist) for polyps larger than 10mm, ranging from 75%–91% and 90%–93%, respectively, as reported by per-polyp comparisons [3, 4, 12]. More recently, the largest multicenter independent clinical trial was conducted in the National Naval Medical Center, Walter Reed Army Medical Center, and the Naval Medical Center San Diego. Participants (1,233 asymptomatic subjects) received a VC examination followed the same day by optical colonoscopy. The results of the study show 93.9% sensitivity and 96.0% specificity for polyps 8mm and larger [9]. These results demonstrate that VC performance compared very favorably with that of optical colonoscopy, the accepted standard. Subsequently, the U.S. Food and Drug Administration approved VC as a screening tool for detecting colon cancer. VC is poised to become the procedure of choice for mass screening for colon polyps, the precursor of colon cancer. If all patients 50 years of age and older will participate in these screening programs, over 92% of colorectal cancer will be prevented. C

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