Automatic Segmentation, Tissue Characterization, and Rapid Diagnosis Enhancements to the Computed Tomographic Colonography Analysis Workstation

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An image processing system developed to support examination of computed tomographic colonoscopy (CTC) was developed in 1995. The clinical viability of CTC is enhanced by the solution of several technical problems. These problems include the limited detectability of sessile polyps and difficulties in discrimination between polypoid masses and retained stool. CTC is also made more feasible by simplifying the required colon preparation and reducing the time required to analyze scan results. Each of these challenges have been addressed by enhancements to the CTC analysis workstation software. Endoluminal volume rendering has been enhanced by the addition of automatic segmentation to facilitate analysis of colon segments, which contain tagged liquid stool. By automating this function, the system is able to process scans that are acquired following a wide variety of colon preparation protocols. Similar approaches have been used to identify retained stool. Automatic tissue characterization has also been incorporated into the volume rendering routines to help identify and diagnose polypoid masses. These enhancements have improved the quality of CTC interpretation, while reducing the time required to perform the analysis. This time reduction was necessary to reduce the cost of CTC enough to make it viable for asymptomatic population screening. To date, over 150 patient examinations have been performed using this new technique. A recent blinded, prospective study reporting the results from two independent observers has been presented. The technique is feasible, reliable, and has been implemented clinically with results reported within 1 hour of the examination.

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COMPUTED TOMOGRAPHIC COLONOGRAPHY (CTC) is an emerging technique for detecting colon polyps. Colon cancer is a major cause of death in industrialized nations. Because colon cancer develops from adenomatous polyps, detection and removal of these polyps greatly

reduces the risk of developing colon cancer. Currently available colorectal screening tests are imperfect. The potential use of CTC as a screening test holds great promise.

A CTC examination involves the use of a helical CT scanner to image the lower abdomen of a patient whose colon has been purged and insufflated with carbon dioxide.¹ Imaging is typically performed with 5 mm collimation, table speed of 7.5 mm per second, and a reconstruction interval of 3 mm. This results in approximately 150 tomograms, or 40 million voxels, per scan.

CTC Interpretation System

CTC is the first clinical procedure to employ a combination of cross sections and rendered images for primary interpretation of a radiological examination. A custom image analysis system has been developed at our institution² for CTC interpretation. This system simultaneously presents axial sections, rendered scout views, transcolonic cross sections, and two intraluminal perspective views. It has been shown that the use of this system is more reliable than the interpretation of the axial tomograms alone.³ To achieve acceptable performance, a novel volume rendering technique was developed.

Objective

The purpose of this report is not to present the results of clinical trials of CTC. These have been reported elsewhere.^{1,4,5} Rather, a detailed explanation of the custom workstations software that has made this research possible is presented.

HYPERLIST VOLUME RENDERING

Lossless Data Reduction

When there are a finite number of possible viewpoints, the need for translucence is limited, it is possible to select a set of voxels, which will contain all visible surfaces. In a typical CTC examination where all viewpoints are within the insufflated colon and rendering depths can be limited to 12 cm, the set of all possible surface

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voxels contains only about 5% of the voxels in the scan.

In renderings with step function opacity maps, a voxel may only lie on a visible surface if its value is either greater than all voxels between it and the viewpoint, or is less than all those voxels. This, of course, is true regardless of the threshold. To find these voxels, rays are cast out in all possible directions from each possible viewpoint. Along each of these rays, all voxels whose value is either greater than or less than all previously encountered voxels along the ray are identified.

A list is generated that contains the coordinates of each identified voxel. The value of the voxel and that of the last previously identified voxel are also stored. These values form the upper and lower bounds on threshold values for which the selected voxel lies on a visible surface. These data are extracted for each viewpoint and the resulting list is sorted by position. Points that are visible from multiple viewpoints will have several adjacent elements in this list. These redundant data are compressed into a single entry with the maximum range of threshold values and the range of consecutive viewpoints noted. The remaining data are then reordered by initial viewpoint.

Dynamic Transformation of Candidate Surface Voxels Into Hyperlists

During interactive interpretation, a complete list of potentially visible voxels is maintained. As the point of view is interactively moved, the voxels, which have become obscured, are released and those that will soon come into view are loaded. In most cases, the buffer is large enough to contain about twice as many voxels as could be seen from a single viewpoint. This dynamic buffer is managed by a separate processing thread, which keeps the segment of the colon whose surfaces are loaded approximately centered over the current viewpoint.

This loaded voxel list is stored in a data structure known as a "hyperlist". This structure is unique from a conventional voxel list much as hypertext is different from plain text. This difference is that links connect related element in diverse sections of the structure. This data structure is also different from a linked list in several powerful ways. Perhaps the most important difference is in how the links are formed. Every element in the structure is accessible even when a minimum number of links are present. However, whenever an element is

chosen (in this case, selected for transformation into the rendered scene), additional links are generated, which associate the selected voxel with others. A single index is also maintained, which identifies the voxels that are visible in the most recent rendering.

The hyperlinks form a four-dimensional mesh. Two of these dimensions relate to coordinates in the rendered image. The others are aligned with viewpoint number (distance along the colon midline) and with depth or threshold value. These last two dimensions correspond to parameters, which are constant throughout an entire rendered scene. Because both of these parameters are never simultaneously manipulated, the hyperlist links form mainly along orthogonal planes within this parameter hyperspace. Movements along these planes become increasingly efficient. This leads to rendering performance similar to that achieved by algorithms, which use depth buffer recycling without the associated erosion of resolution. While selected voxels remain within the hyperlist, the number of links increases making the link mesh progressively more intricate and powerful. Thus, while a selected region of the colon is explored, the rendering speed increases.

Rendering from Hyperlists

Hyperlinks are always maintained that connect voxels into strings, which form line of sight rays through each pixel in the scene to be rendered. These links are formed whenever the viewpoint is altered. To do this, the voxels are divided into six sectors and sorted by direction and distance from the viewpoint. The precision of the integer direction components are varied with depth. This causes the rendering to be performed at nearly constant resolution. By avoiding excessive oversampling of the foreground, rendering speed can be enhanced without loss of detail.

When a single opaque surface is rendered with depth and gradient shading (as is typically used in CTC), pixels are rendered by simply scanning corresponding hyperlists for the depth of the threshold crossing and interpolating shading values into the rendered scene. Additional links are created, which associate the selected depths among adjacent rays. These new links make it possible to render previously observed areas of the view field without searching along depths (ray tracing). The use of these alternate links is similar in complexity to

two-dimensional geometric transformation with bilinear interpolation. Similar hyperlinks are also generated when the viewpoint is altered. Thus, rendering speed is significantly enhanced when the traversal of a segment of the colon midline is repeated.

Other Applications of Hyperlist Rendering

The hyperlist volume rendering algorithm has been presented as a fast method for rendering perspective scenes with depth or gradient shading, which contain opaque foreground objects. Indeed, it was developed specifically for this purpose. However, it is also quite efficient at rendering with a variety of other shading techniques and is adaptable to many other applications.

AUTOMATIC SEGMENTATION BY HYPERLISTS

Differentiation between the gas insufflated into the colon lumen and the mucosal surface of the colon is almost trivial. However, the lavage preparation required before CTC often leaves significant fluid within the colon. This liquid can obscure the colon surface and lesions because it is usually isodense with soft tissue. The automated segmentation performed by hyperlist rendering, combined with the administration of an oral stool marker, could help in solving this problem.

Processing of Retained Liquid

Bowel segments filled with contrast enhanced liquid are processed without difficulty. Negative threshold crossings are processed just as positive ones are. The voxel at the viewpoint is always considered transparent. When the colon midline passes beneath the surface of a pool of liquid contrast, the definition of the wall automatically switches and the liquid/mucosal surface is rendered. An additional benefit of this feature is that evaluation of contrast-enhanced vascular structures is also supported by this system.

TISSUE CHARACTERIZATION FROM HYPERLISTS

There are two aspects of tissue characterization that apply to CTC. These include the classification of identified polypoid masses and the identification of subtle mural masses, which might be overlooked

due to their unremarkable appearance on both cross-sectional and rendered images.

Classification of Polypoid Masses

There is a need to evaluate polypoid masses and determine their true nature. Solid stool is often indistinguishable from polyps in rendered images. Also, some intraluminal masses are benign lipomas, which do not require treatment when fully characterized. While these abnormalities can have similar shapes, they have different internal morphology. The density of stool is often lower than soft tissue (polyps). Furthermore, stool is usually more heterogeneous than a polyp. Lipomas are composed largely of fat cells. Therefore, their internal density is significantly different from other soft tissue neoplasm. These differences can be determined either from the tomographic images or from the rendering hyperlist. The hyperlists could potentially be used to structure rigorous definitions for automatic differentiation. Much additional effort is needed to fully realize the potential of this application of hyperlists.

Detection of Subtle Mural Masses

It has been reported⁶ that flat polyps can be automatically identified by measuring mucosal thickness or perfusion. If such measurements do prove useful, the hyperlist rendering algorithm will be very effective because of its inherent encoding of these parameters.

CONCLUSION

CT colonography is a new method of assessing the colorectum for neoplastic growths. The system, which we presented 1 year ago, was the first clinically viable method for analyzing these examinations. That system has now been used to evaluate over 150 CTC examinations. Many of these have been processed multiple times by different radiologists for training purposes and to assess interobserver variability.⁴ Although the performance of available workstations has improved substantially during this period, these improvements have been far outpaced by increases in workload. This trend is expected to continue for several years.

The purpose of this report has been to describe a unique method of volume rendering that was developed to meet CTC's specific requirements for high resolution interactive volume rendering. This

technique, referred to as “hyperlist volume rendering”, is voxel list based and generates a multiple dimensional link mesh. In this way, endoluminal perspective renderings with dynamic surface defini-

tion can be generated and displayed at interactive speeds on low cost workstations. Lesion detection and characterization is also possible using the described system.

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