# Virtual bronchoscopic approach for combining 3D CT and endoscopic video

Anthony J. Sherbondy,[a] Atilla P. Kiraly,[a] Allen L. Austin,[a] James P. Helferty,[a] Shu-Yen Wan,[a] Janice Z Turlington,[a] Tao Yang,[a] Chao Zhang,[a] Eric A. Hoffman,[b] Geoffrey McLennan[b] and William E. Higgins*[ab]

[a]The Pennsylvania State University, University Park, PA 16802, USA
[b]University of Iowa, Iowa City, IA 52242, USA

## ABSTRACT

To improve the care of lung-cancer patients, we are devising a diagnostic paradigm that ties together three-dimensional (3D) high-resolution computed-tomographic (CT) imaging and bronchoscopy. The system expands upon the new concept of virtual endoscopy that has seen recent application to the chest, colon, and other anatomical regions. Our approach applies computer-graphics and image-processing tools to the analysis of 3D CT chest images and complementary bronchoscopic video. It assumes a two-stage assessment of a lung-cancer patient. During Stage 1 (CT assessment), the physician interacts with a number of visual and quantitative tools to evaluate the patient's "virtual anatomy" (3D CT scan). Automatic analysis gives navigation paths through major airways and to preselected suspect sites. These paths provide useful guidance during Stage-1 CT assessment. While interacting with these paths and other software tools, the user builds a multimedia Case Study, capturing telling snapshot views, movies, and quantitative data. The Case Study contains a report on the CT scan and also provides planning information for subsequent bronchoscopic evaluation. During Stage 2 (bronchoscopy), the physician uses (1) the original CT data, (2) software graphical tools, (3) the Case Study, and (4) a standard bronchoscopy suite to have an augmented vision for bronchoscopic assessment and treatment. To use the two data sources (CT and bronchoscopic video) simultaneously, they must be registered. We perform this registration using both manual interaction and an automated matching approach based on mutual information. We demonstrate our overall progress to date using human CT cases and CT-video from a bronchoscopy-training device.

**Keywords:** virtual endoscopy, virtual bronchoscopy, CT bronchography, 3D imaging, pulmonary imaging, high-resolution CT, volume visualization, computer-assisted surgery, image-guided surgery, virtual reality

## 1. INTRODUCTION

The standard procedure for diagnosing lung cancer and many other intrathoracic diseases involves three-dimensional (3D) X-ray CT assessment followed by bronchoscopy.[1] Electron-beam CT (EBCT) and helical (spiral) CT scanners provide high-resolution 3D images of the chest.[2] These images give visual data for detecting lung cancer and can aid the bronchoscopist in constructing a roadmap to perform biopsies and treatment. The basic procedure in examining a patient is to first analyze the 3D CT image for any suspect sites (locations of possible lesions or suspect lymph nodes) and then mentally plan a path to that site for the bronchoscopist to follow. Once the bronchoscope is inserted, the site may be biopsied or treated. Analysis of the 3D images is still done manually in clinical practice. Resultant images are mentally interpreted slice by slice. All interactions with the data, from identifying suspect sites to planning a path to a suspect site, occur in 2D and are done manually.

A new field, virtual endoscopy, has emerged to allow more information to be extracted from 3D images. Proposed approaches for virtual endoscopy permit 3D endoluminal renderings, global 3D structural renderings, multiplanar reformatted 2D slice views, and others for augmenting the physician's vision for 3D image assessment and planning.[3–9] Focusing on the chest, this field is referred to as virtual bronchoscopy (VB). (We point out that virtual endoscopy and VB are often focused on generating mere endoluminal renderings. This need not be the case, as computer-graphics offers many possibilities for improving the physician's vision of a case.[1,10,11])

VB is a new field and most effort to date has focused on 3D image assessment only.[1,7,9–15] Despite the potential benefits thus far demonstrated for VB, no definitive set of tools and protocols have yet to be defined to fully exploit the diagnostic potential of VB for 3D radiologic image assessment. Further, only incipient efforts have been made to integrate VB with follow-on bronchoscopy.[16–18]

We believe the ideal scenario for performing a complete VB-based examination of a pulmonary-disorder patient must tightly couple the processes of 3D image assessment and follow-on bronchoscopy. VB-based image assessment needs to provide a complete CT exam, consisting of a *stored case report.* This report need not be restricted to

*Correspondence: Email: weh2@psu.edu; WWW: http://gehrig.ee.psu.edu/; Telephone: 814 865 0186; Fax: 814 863 5341

standard text and radiographic film. It can contain various visual views, movies, and quantitative summaries of the case. It must also provide a follow-on assessment and treatment plan for bronchoscopy. During bronchoscopy, the physician should be able to get *direct quantitative and visual guidance* beyond the bronchoscopic video on precisely where and how to perform tissue biopsy or treatment.

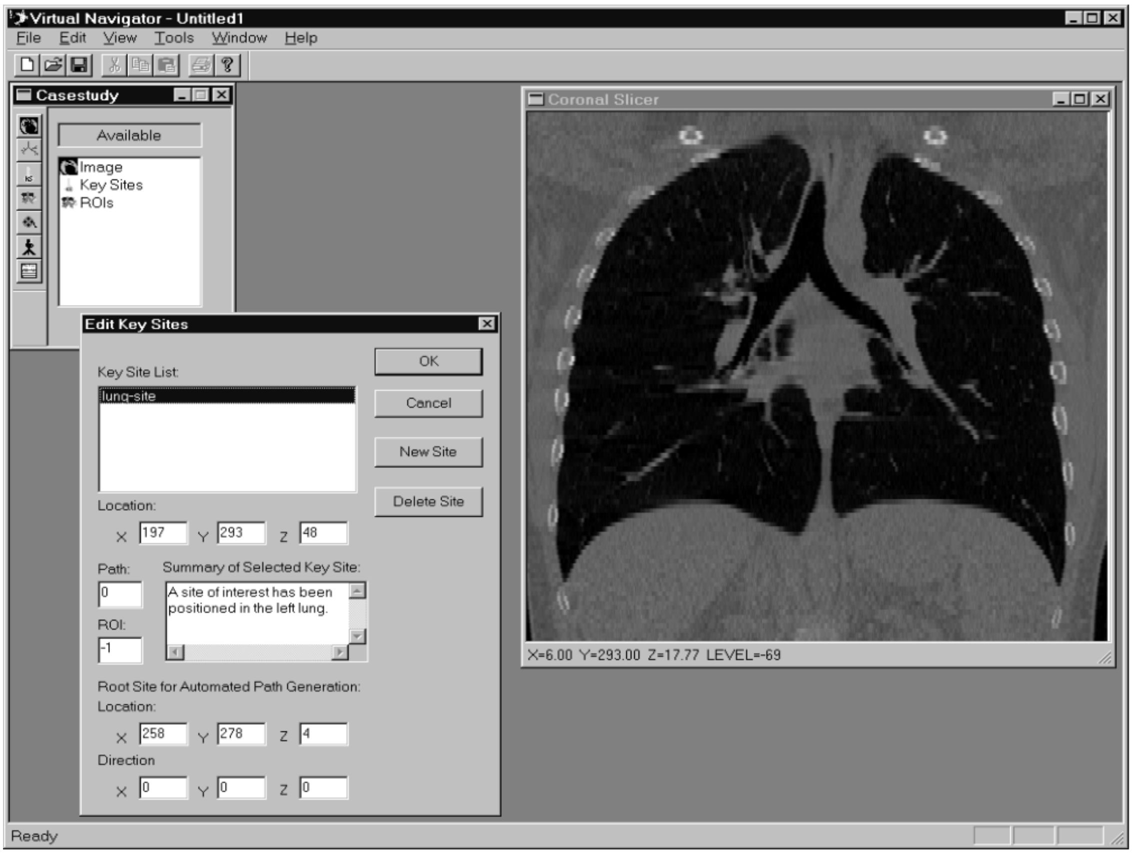



**Figure 1.** Defining the data necessary for running tree analysis. Upper left corner displays the *Case Study Manager.* The *Coronal Slicer* tool presents a 2D ($x$-$y$) MPR slice through the chest. The user points the mouse to any acceptable point near the proximal end of the trachea (dark vertical tube near the center of the view) to specify a root site. This information is recorded as a new data abstraction for the Case Study in the *Edit Key Sites* panel (part of the *Case Study Manager*), as shown. (An optional key site was also defined as an example, with additional text data.) After this data is defined, the data abstractions pertaining to the tree can then be computed

We present our progress on an integrated computer-based paradigm for complete VB-based CT-bronchoscopy chest assessment and treatment delivery. We provide the physician with a number of graphics and image-analysis tools to carry out a complete patient examination. Our approach assumes a two-stage assessment of a lung-cancer patient and centers around the concept of a multimedia *Case Study.*[19] The Case Study can contain many graphical and quantitative components in addition to the usual text-based report. (Others have also recently proposed the concept of a multimedia case study for 3D radiologic image assessment.[14,20]) The Case Study also acts as a "roadmap" during bronchoscopy to provide an "augmented reality" to the bronchoscopist.[1]

The two stages of our approach are as follows. During *Stage 1 (CT assessment)*, the physician interacts with visual and quantitative tools to evaluate the "virtual anatomy," as embodied by a patient's 3D CT scan. During this stage, the physician builds the Case Study. During *Stage 2 (Bronchoscopy)*, the physician can use the "roadmap" information in the Case Study for bronchoscopic assessment (e.g., tissue biopsy) or treatment (e.g., stent design and placement). All tools for CT assessment and bronchoscopy run interactively on an inexpensive personal computer (PC). The Case Study is built on the PC. Automatic analysis provides considerable guidance and quantitative data for building the Case Study. Thus, complete Stage-1 CT assessment can be done in minutes. The bronchoscope is linked to the PC through a standard frame-grabber board. A critical step in using the two data sources (CT and bronchoscopic video) simultaneously during live bronchoscopy requires precise interactive registration of the CT data to the position of the bronchoscope. Our approach to performing this registration involves both manual interaction and an automated matching approach based on mutual information.

Section 2 of this paper overviews the complete two-stage CT-bronchoscopy approach. Section 3 uses two human cases to illustrate the elements of building a Case Study during Stage-1 CT-only assessment. Progress to date on devising the complete two-stage approach, using a rubber bronchoscopy training model, is detailed in Section 4. Finally, Section 5 offers concluding remarks.

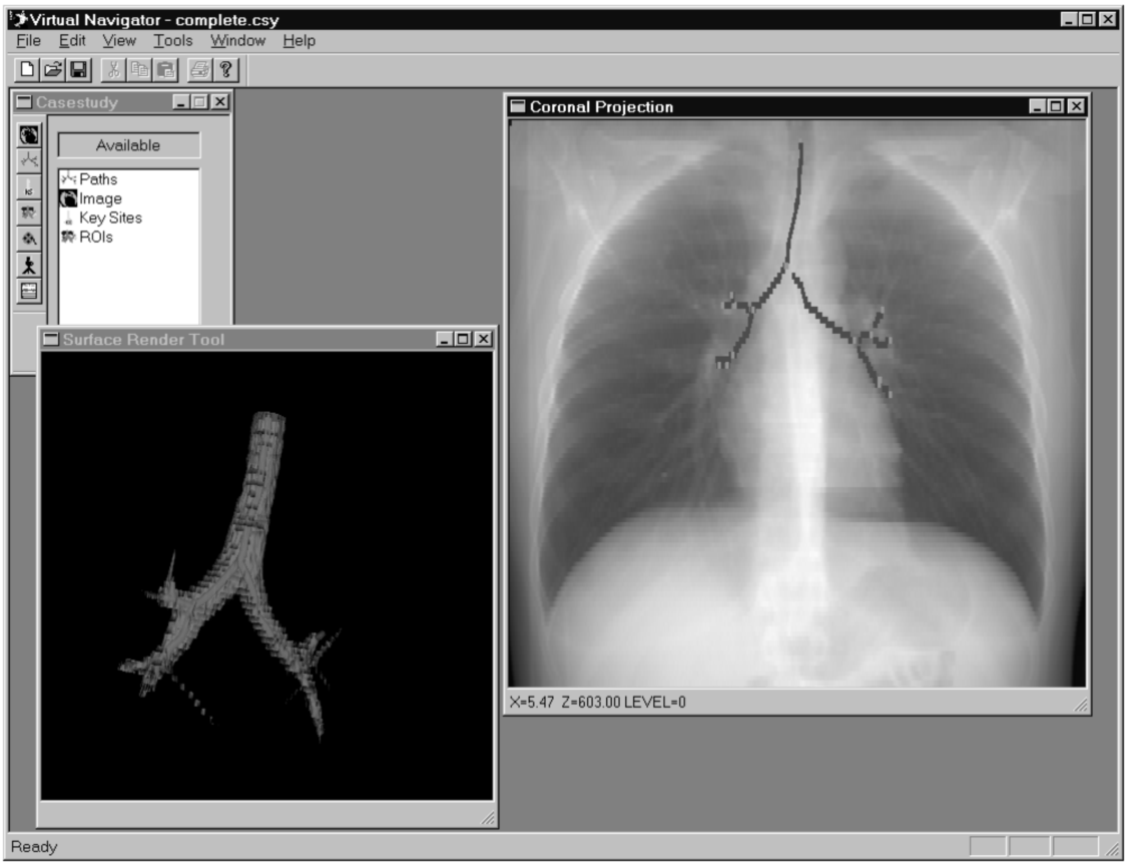


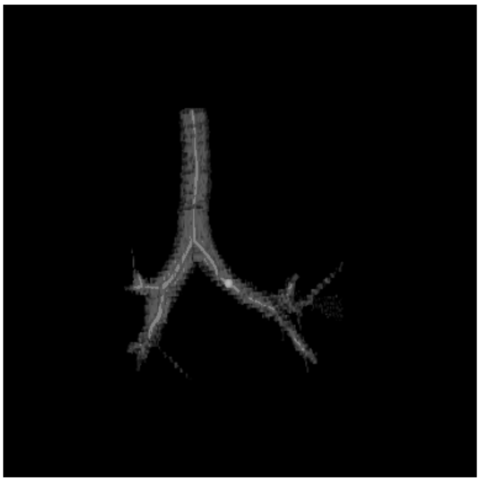

**Figure 2.** Beginning the formal building of reporting abstractions. The *Surface Render* tools shows the segmented airway tree along with the its computed axial structure (depicted as solid lines superimposed on the rendered airway tree). The weighted-sum *Coronal Projection* tool also shows the computed tree projected onto the coronal ($x$-$z$) plane; the solid squares on the tree are branch (bifurcation) points of the tree. These global tools in tandem with the tree data abstractions provide systematic navigation capability during Case-Study construction.

## 2. VB-BASED CT-BRONCHOSCOPY PARADIGM

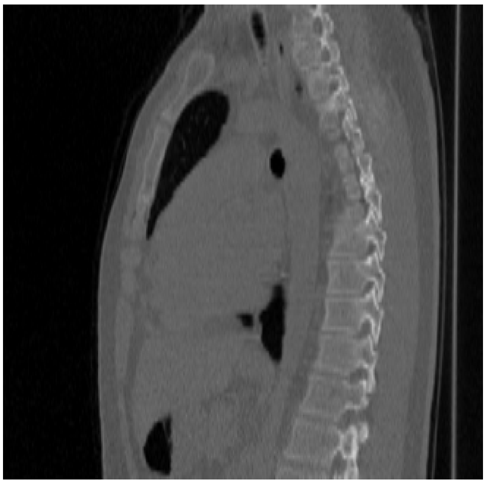
This section describes the basic two-stage procedure for performing a complete two-stage CT-to-bronchoscopy examination. Section 2.1 presents the visualization and analysis tools available for building a Case Study and performing an examination. Section 2.2 describes the elements of the Case Study. Finally, Section 2.3 outlines how to perform a complete two-stage examination from initial CT scan to final bronchoscopy.

### 2.1. Visualization and Analysis Tools

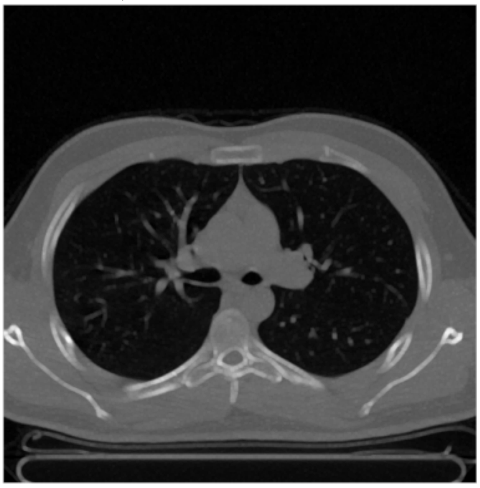
A suitable VB assessment of a lung-cancer patient undoubtedly requires more than just the traditional rendered endoluminal views. For VB-based CT-video assessment, our approach provides a wide range of visual and quantitative tools. These tools offer a variety of viewing, quantitation, and documentation options and greatly facilitate building a complete Case Study. Below is a list of the available tools:



a) *Surface Render* tool

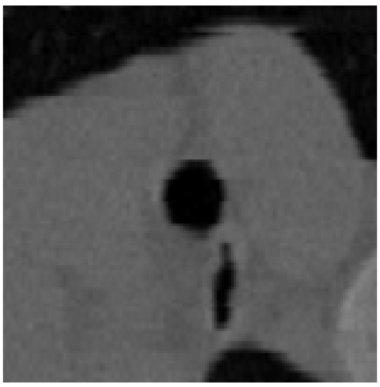


b) *Sagittal Slicer* tool

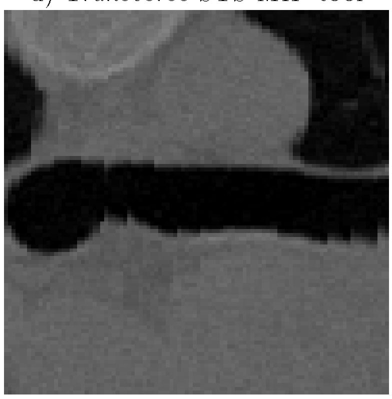


c) *Transverse Slicer* tool

d) *Transverse STS-MIP* tool



e) *Orthogonal Cross-Section* tool



f) *Longitudinal Cross-Section* tool

**Figure 3.** A variety of static tool views for a viewing site selected from the *Surface Render* tool's tree. (a) *Surface Render* tool view, showing rendered airway tree and the axial tree representation; the solid ball on a path passing through left main bronchus of this tree is a manually picked site (using the mouse); all following views pass through this viewing site. (b) *Sagittal Slicer* view. (c) *Transverse Slicer* view. (d) *Transverse STS-MIP* view. (e) Orthogonal *Cross-Section* tool, which shows a local view perpendicular to the viewing site of interest. (f) Longitudinal *Cross-Section* view, parallel to the viewing site of interest.

*Case Study Manager* - Interactive clearinghouse for constructing the Case Study.

*Virtualscope* - Provides computed endoluminal volume-rendered views. The views are computed interactively based on rapid coherence-based volume rendering that requires no prior image segmentation or surface definition.[21]

*Projection Tools* - Gives either weighted-sum or maximum-intensity 2D projection images of the complete 3D CT image. Views from the coronal, sagittal, and tranverse directions are available.

*Surface Render Tool* - Presents a 3D surface-rendered view of the airway tree. The surface representation is calculated off-line, prior to analysis, using a segmented airway tree provided by the *Tree Analysis Tool* and by using the standard marching-cubes surface-rendering algorithm.[22]

*Slicer Tools* - Gives transverse, sagittal, and coronal multiplanar reformatted (MPR) ("slicer") views (i.e., 2D slice images along the standard $x$, $y$, or $z$ axes).[2]

*Cross-Section Tools* - Provides local cross-sectional images passing through interior viewing sites of interest. Views are available through a local plane either parallel or perpendicular to the viewing site of interest.

*Sliding Thin Slab (STS) Tools* - Gives transverse, sagittal, and coronal sliding thin-slab (STS) rendered views. The standard STS-MIP view and newly devised depth-weighted maximum and extreme-gradient STS views are available.[23]

*2D Plot Tool* - Provides a 2D plot of quantitative data computed along a navigation path.

*Tree Analysis Tool* - computes a wide variety of guidance and quantitative data for the 3D airway tree.

*Video Match Tool* - Used during bronchoscopy, it displays the bronchoscopic video and corresponding matching surface-rendered CT-based endoluminal view. It enables CT-guided bronchoscopy and performs the registration between the bronchoscopic video and CT data.

Nearly all tools can be active simultaneously while building a Case Study. This provides a diverse environment for saving the information desired. Further discussion on the use of the tools appears in Section 2.3.

All software tools run on standard PCs using Windows 98 or Windows NT 4.0. Development and testing was done with the Windows NT 4.0 operating system, running on a 450MHz Pentium II class machine (384 MB of RAM, 18 GB of hard drive space). A Matrox Meteor II frame-grabber PCI card interfaces to the bronchoscope's video output. Currently, such systems cost about $3,000, including the frame grabber. All code was written using Microsoft Visual C++ 5.0 and MFC. The C++ STL was used extensively for data storage, retrieval and manipulation. OpenGL and vtk were used for much of the graphics development.[22] The top-level software for the approach and associated tools conform to an object-oriented framework developed in the Unified Modeling Language using Rational Rose.[24,25]

Many of the tools above have been proposed in some form previously for VB-based radiologic image-assessment systems implemented on Unix-based worktstations. A previous system we have devised for Sun workstations incorporated the *Virtualscope*, *Projection* tools, *Slicer* tools, and *Cross-Section* tools.[1,21] Also, other proposed systems have given tools such as the *Surface Render* tool[11,26,15] and *Slicer* tools (MPR views).[5,10]

It is well acknowledged that precomputed guidance data are required for effective virtual-endoscopic evaluation of a 3D radiologic scan.[1,27–29] Such data become even more critical for a complete VB-based CT-to-bronchoscopy patient assessment. Our *Tree Analysis* tool provides the following quantitative guidance data:

1. Smooth central axes and labeled branch (bifurcation) points for the major airway branches.
2. Cross-sectional area measurements along the extents of the extracted airway branches.
3. Paths to predefined *key sites.*
4. Segmented airway tree.

As discussed further in Section 2.3, the *Tree Analysis* tool uses easily defined *root-site* and *key-site* data to perform these calculations. It uses a procedure, based on local incremental ray casting, contour definition, and spline analysis, to define the desired analysis data rapidly. For the cases presented in Section 3, the *Tree Analysis* tool computes the desired guidance data in several minutes on a standard 450 MHz PC. A recent paper[30] gives a complete description of the *Tree Analysis* tool's methodology, with earlier work[31,32] discussing many of the fundamental underlying ideas.

### 2.2. Case Study

The Case Study serves as both a multimedia report of a given 3D CT scan and as a supplemental plan for bronchoscopy. The elements of a Case Study can be divided into three categories: (1) *data sources*, (2) *data abstractions,* and (3) *reporting abstractions.* The data sources consist of raw information input from the CT scanner and bronchoscope. The data abstractions capture specific key details on interesting thoracic structures. They facilitate navigation through the chest, and they provide quantitative and structural data for regions of interest. The data abstractions are created and modified using the software tools and the input data sources. In general the software tools require both the data sources and certain data abstractions to function. Finally, the reporting abstractions are created by the user specifically to be saved with the final Case Study. They capture the physician's interpretations and thoughts on the case, and they may take a visual, quantitative, or textual form. The following list details the elements of a Case Study:

1. **Data Sources**

   *Image* - The 3D CT image of the patient's chest.

   *Bronchoscopic Video* - The video stream of the bronchoscope.

2. **Data Abstractions**

   *Root Site* - A 3D location that marks the beginning of the airway tree. It is generally within the trachea.

   *Key Site* - A 3D location marking an area of interest in the image (e.g., site of a narrowing or suspect lymph node). A key site need not be located within an airway.

   *Viewing Site* - Specifies a viewing/navigation location within a 3D image. A viewing site consists of a 3D position and 3D viewing direction.[21]

   *Path* - A 3D navigation path within the 3D image. It consists of a sequence of viewing sites originating from the root site and terminating at either an airway branch endpoint or a key site. If the key site is within a solid tissue region (e.g., it corresponds to a mediastinal lymph node site), then the computed path will stay within the airways s long as feasible and then "burst" through the airway wall to the site; such a path corresponds to the path that a real bronchoscope must follow for a needle biopsy (transbronchial needle aspiration or TBNA).

   *ROI* - (Region Of Interest) - A segmented region of diagnostic significance (e.g., the airway tree or a cancer nodule).

   *Tree* - Detailed branching and geometrical information of the segmented tracheobronchial tree. It consists of a labeled sequence of paths and a segmented airway tree.

3. **Reporting Abstractions**

   *Snapshot* - Captured display of a tool view.

   *Plot* - Labeled 2D graph of cross-sectional area along a specific airway path.

   *Measurement* - Numerical measurement of a labeled area of interest, along with a textual description. The measurements are made by positioning graphical calipers on key sites of *Slicer* tool views. An example would be a measurement of a narrowed airway in the vicinity of the stenoses.

   *Movie* - Captured dynamic image sequence from a tool. A movie is formed from a consecutive sequence of tool views along a path.

   *Case Notes* - Additional text input documenting the case.

A Case Study in general requires one root site. There is no restriction on the number of key sites, snapshots, plots, measurements, and movies. A Case Study can be reevaluated and altered at any time. The next section discusses how a Case Study is built, and Sections 3 and 4 give examples.

### 2.3. Performing a Complete Examination

*Stage-1: CT Assessment* – A Case Study begins with the input 3D CT chest image. To proceed in building a Case Study, the user manually specifies a root site and one or more key sites to potential suspect regions. The *Tree Analysis* tool then computes the tree and all of its associated components, per Section 2.1. It also generates individual paths beginning from the root site and terminating at each key site.

All of this guidance data assists the user in constructing the desired reporting abstractions. Generally, to begin this construction, the user invokes the weighted-sum *Coronal Projection* tool and *Surface Render Tool.* These tools, which act as global references to the shape of the thoracic structures, depict the extracted tree and key-site paths.

The user now more formally begins the process of examining the case and building a possible bronchoscopic assessment plan. Other tools are started. The user now graphically selects individual viewing sites, paths, or sections of paths depicted in the *Projection* or *Surface Render* tools. If the *Plot* tool is invoked for a specific path, the user can also select individual viewing sites on the plot to view in other tools. In general any number of tools or any number of instances of the same tool can be invoked while performing this analysis. Nearly all tools are dynamic. For example, if the user selects a specific path, all tools will present views simultaneously and dynamically as a movie sequence along the selected path. In this way, the user gets a sophisticated multipart display of the structure and characteristics of the case. If a particular tool view or movie has diagnostic significance, the user can save this element as part of the Case Study. Also, particular observations can be recorded as text through the *Case Study Manager*, as is traditionally done in 3D radiologic image assessment. When the user finishes the VB examination, he can move on to bronchoscopy if needed.

*Stage 2: Bronchoscopy* – We will describe the scenario of performing a tissue biopsy for a suspect site. With the bronchoscope's video output interfaced to the computer, the user loads the Case Study built during the Stage-1 assessment. The *Coronal Projection* and *Surface Render* tools are invoked, with the tree and and with the precomputed path to the key site depicted. Also, at this point, the *Video Match* tool and *Virtualscope* are begun. The user now selects a viewing site along the key-site path part way down the trachea (e.g., near the carina). This viewing site is then rendered in all tools, except the *Video Match* tool. The user moves the bronchoscope until it roughly corresponds to the current virtual position, as depicted in the other active tools. The bronchoscope's view–i.e., it's video ouput–appears in the *Video Match* tool's display.

The user then moves further down the key-site path, say, for example, to a viewing site just past the carina in the left main bronchus. The user does this by selecting another viewing site of the key-site path on either the *Coronal Projection* or *Surface Render* tool. This is analogous to moving a virtual bronchoscope through the airway tree within the virtual environment of the 3D CT scan. After this virtual movement, the user then moves the real bronchoscope roughly to the same position. The user iterates this process until he has approached the wall that must be punctured to make the tissue biopsy.

At this juncture, the *Video Match* tool then performs an iterative mutual-information-based matching between the rendered 3D CT data and current bronchoscope view to precisely register the CT to the bronchoscope. Basically, the coordinate system of the virtual environment is centered about and registered to the current real in vivo position of the bronchoscope. During this matching, we assume that the bronchoscope is stationary and that the virtual position within the 3D CT-image environment undergoes adjustment. This takes the burden off the human to position the device precisely. When the registration is complete, the user can then observe views in other tool views or in snapshot views saved earlier to plan an entry point for the biopsy needle. The tools and captured views provide extra anatomical information to the bronchoscopist outside the field of view of the bronchoscope.

## 3. CT-ONLY EXAMPLES (STAGE 1)

This section offers two stage-1 CT-assessment examples. The first example emphasizes the operation of the global navigation tools and tree analysis. The second case provides validation of our approach's ability to quantitatively assess airway abnormalities. Section 4 discusses progress on performing a complete two-stage examination.

### 3.1. Healthy Human

An Imatron EBCT scan was performed on a healthy adult female. The subject held her breath for one 20-sec breath-hold during the scan. Her lung volume was held at 90% TLC using a lung-volume controller.[1] The resulting 3D CT image contained 115 contiguous slices, with each slice consisting of 512×512 voxels (slice thickness = 3.0mm, axial-plane [x-y] resolution = 0.684mm).

The 3D EBCT image was loaded into a new Case Study. The user then defined a root site, which roughly marked the proximal end of the trachea. The 2D MPR view offered by the *Coronal Slicer* tool offers an easy interactive mechanism for defining this site. See Fig. 1. After the root site is defined, the *Tree Analysis* tool computes the tree data. For this case, the analysis required approximately 5 minutes on a 450MHz PentiumII PC.

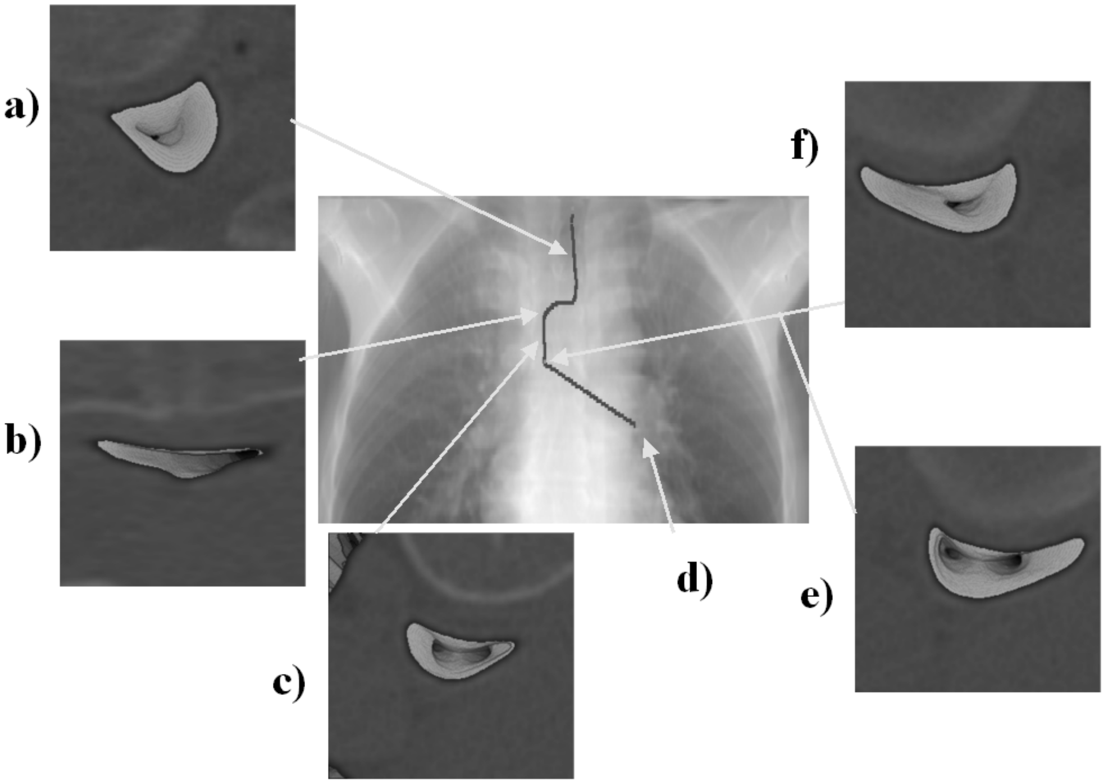
The formal building of the report can now begin. The guidance data from the *Tree Analysis* tool, now a part of the Case Study, is displayed in the *Coronal Projection* and *Surface Render* global-reference tools, as shown in Fig. 2. Other tools of interest can also now be started at this time. The user can then select individual viewing sites, a branch, or complete path of the airway tree interactively on either of the two global-reference tools. The other activated tools then synchronously display the information–be it a static view, plot, or dynamic movie–for this selection. See Fig. 3. Views, such as those shown in Fig. 3, movies, measurements, and other annotations can be saved with the Case Study. The next example highlights some of the useful diagnostic observations that can be made.

### 3.2. Pathology Case

A patient suffering from tracheomalacia (collapsed trachea) underwent an EBCT scan. Using a single 20-sec breath-hold, a 3D EBCT image made up of 133 contiguous slices was reconstructed. Each slice consists of 512×512 voxels (slice thickness =1.5mm; axial-plane [x-y] resolution = 0.586mm).

After creating a new Case Study using the EBCT image, the user selected a root site near the proximal end of the trachea and a key site beyond the location of the collapse. The user quickly gained an impression of the abnormality by perusing the 3D image data in the *Coronal Slicer* tool. Selection of the root site and key site are straightforward, and considerable leeway exists in picking these sites. A path from the root site to the key site was then generated using the *Tree Analysis* tool.

Once the path was generated and the airway tree had been segmented, the visualization tools then provided a detailed inspection of the narrowed trachea. Fig. 4 presents such an inspection with multiple endoluminal volume-rendered views, generated by the *Virtualscope*, along selected viewing sites of the computed path. This visualization approach provides a qualitative assessment of the suspect area that could not have been achieved from 2D views alone. This assessment can be done quickly, because the tree analysis gave the quantitative guidance data in only a few minutes. Alternatively, the user could have begun visualizing the narrowing by relying on the quantitative data provided by the *Plot* Tool as Fig. 5 depicts. This figure shows revealing cross-sectional assessments of the pathology obtained by clicking on interesting sites in the cross-sectional area plot of the generated path. These two visualization approaches provide the user with an efficient method for gathering useful information on pertinent regions. The information demonstrated here could conceivably be used for stent design or treatment follow-up.




a) Viewing site #20 approaching tracheal collapse, b) Viewing site #56 within tracheal collapse,
c) Viewing site #86 leaving treachea, d) Key site used to initiate automated tree analysis,
e) Viewing site #99 near carina, f) looking back toward trachea from viewing site #99.

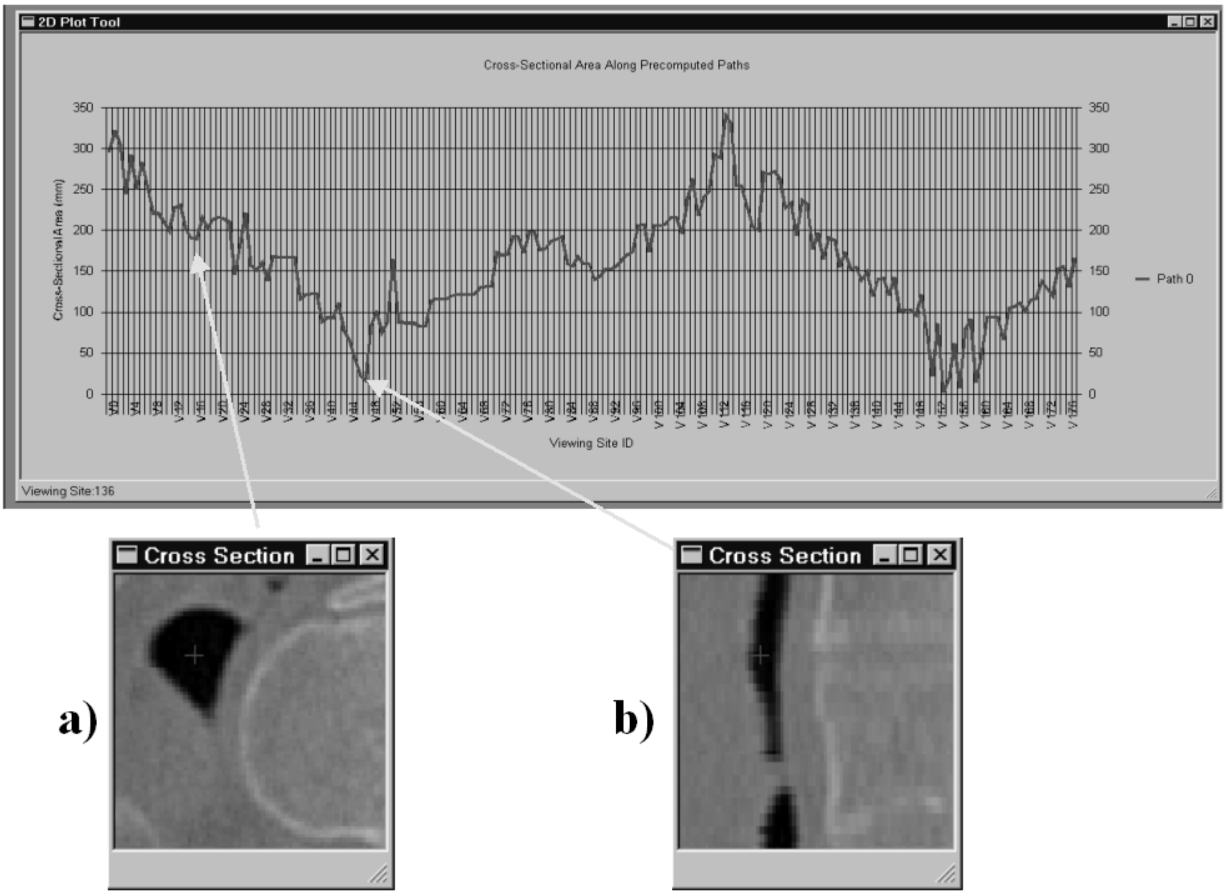
**Figure 4.** Examination of patient suffering from tracheomalacia. Weighted-sum *Coronal Projection* view shows the computed Path, after tree analysis. Multiple labeled endoluminal renderings, computed with the *Virtualscope*, at selected viewing sites illustrate the position, structure, and extent of the abnormality. Note that precise viewing locations are known for the depicted views.

Documentation of the information gathered from the visualization tools can now be recorded and added to the Case Study. As the Case Study matures, movies of any moving image sequence can be saved and annotated as well as telling snapshots that detail the investigation of the case. A full text report of observations and remarks can be placed in the case notes of the Case Study. All of the elements of the Case Study can be graphically managed from the *Case Overview* window.

## 4. PROGRESS IN COMPLETE CT-VIDEO ANALYSIS

Per Section 2.3, we discuss our progress for the complete two-stage VB-based CT-video paradigm for tissue biopsy. Obtaining biopsy samples is a critical step for the diagnosis and staging of lung cancer. A desired procedure is TBNA, where a physician performs either bronchoscopy or mediastinoscopy to sample hilar and mediastinal lymph nodes.[18,33] The difficulty is that these lymph nodes are not visible in the scope's field of view. This leads to a blind procedure where the physician estimates the lymph-node location and puncture point by referencing the CT scan of the patient. Research shows that TBNA is underutilized because physicians have great variability in their skill levels for performing the procedure (they can lose their orientation and point of reference to precisely determine the puncture location).[17,34] Our VB-based paradigm can conceivably alleviate these difficulties.

We demonstrate our results using 3D CT data and bronchoscopic video acquired from a rubber bronchoscopy training device.[35] A 453×155×160 3D EBCT image was generated for this device. Next, a bronchoscopist inserted



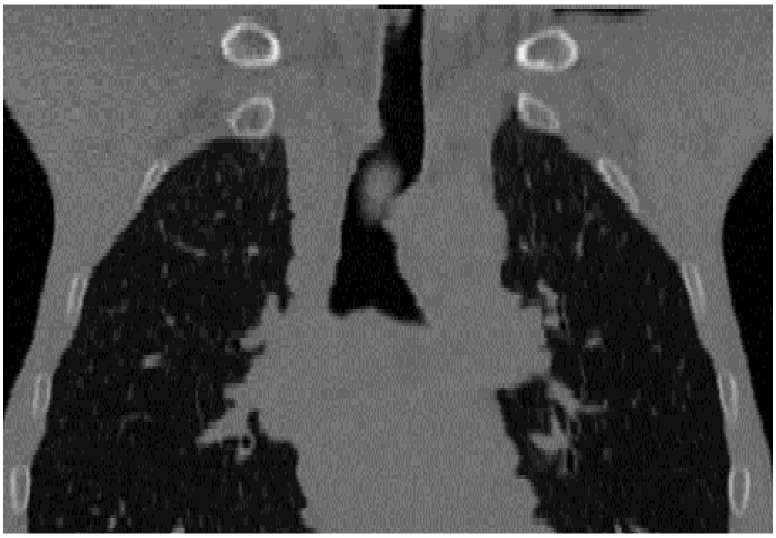

a) orthogonal *Cross-Section* view of viewing site #18 near the tracheal collapse,
b) orthogonal *cross-section* view of viewing site #48 within tracheal collapse.

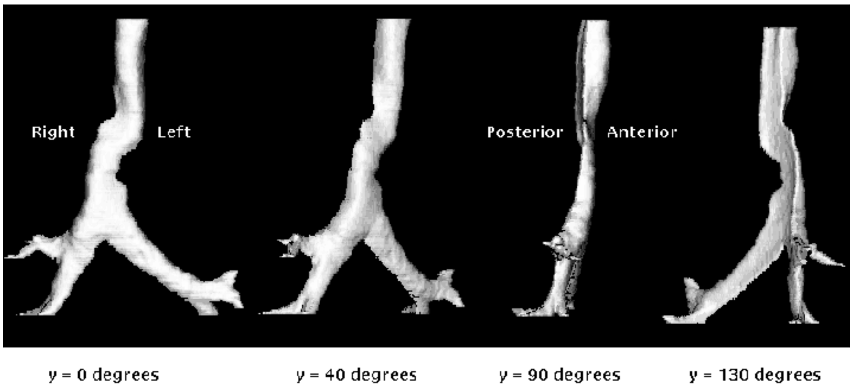
**Figure 5.** Interaction with a plot to focus on viewing information of interest. The *Plot* tool depicts airway cross-sectional area versus viewing site index for the automatically generated path passing through the abnormality (same path as in Fig. 4. By picking a viewing site on the plot, we can observe corresponding views in the other activated tools. The figure shows to two telling orthogonal *Cross-Section* tool views. At site (a), the cross-sectional area is nearly normal and this is corroborated by the cross-sectional image. At site (b), though, the cross-sectional area drops abnormally. The corresponding cross-sectional view visually indicates the tracheal narrowing.

an Olympus fiberoptic bronchoscope into the device, traversed various "airways," and recorded the resulting video. Figure 7 depicts a rendering of the 3D CT data for this device.

Before performing the CT-video "examination" of this device, it is first necessary to correct the bronchoscope's inherent barrel distortion.[36] This distortion, purposely integrated into the bronchoscope's optics to enable wide field-of-view video viewing, must be corrected before it can be matched to the rendered undistorted endoluminal CT data. The user does this by first imaging a known test grid. An algorithm then generates the proper video transformation for correcting the distortion.[37,38] This transformed video data is used by the *Video Match* tool for subsequent CT-to-video matching. Fig. 8 demonstrates the distortion-correction procedure.

As discussed in Section 2.3, for Stage-1 CT assessment, a Case Study is begun, root site and key site points are selected, and a path to the desired biopsy key site is computed. This information is then used during Stage-2 bronchoscopy. Fig. 9 illustrates results. The user progressively moves down the path, selecting viewing sites. These viewing sites are rendered by the *Virtualscope* using the CT data. The user moves the bronchoscope approximately to the site, following the video views presented by the *Video Match* tool.






top) Coronal *Slicer* view showing collapsed trachea,
bottom) Various views of surface-rendered airway tree clearly shows the pathology.

**Figure 6.** Further views of tracheal collapse. The coronal *Slicer* view situated at viewing site #48 (see Fig. 5) clearly shows the collapse region within the trachea. The various rotations of the surface-rendered airway tree (particular at $y = 90^o$ and $y = 130^o$) also give strong visual confirmation on the extent of the collapse. Any of the depicted views can be added as snapshots to the Case Study.

Upon nearly reaching the end of the path near the key site, a matching algorithm is invoked on the rendered endoluminal CT view and the corrected bronchocopic video. The endoscope position and orientation in CT coordinates are calculated using a mutual-information registration criterion.[39,40] The system starts with an initial estimate of the bronchoscope position and viewing direction. As live video is fed into the system, it is registered to a virtual view of the scene from the CT data and estimated scope position. The tracking position that optimizes the mutual-information criteria is deemed the best position of the 3D CT image environment.[41] The Normalized Mutual Information criteria is used for the minimization.[42] This has been found to be effective, since it is a consistent registration criteria when only portions of the two images are consistent. As an added adjustment, entropy terms in the mutual-information calculation have higher weighting on the dark points in the image than the brighter points. This helps matching performance since the lighter areas contain noise from various textures where the darker areas are more consistent between the two images.

## 5. DISCUSSION

We have presented an approach that applies computer-graphics and image-processing techniques to the analysis of 3D CT chest images and complementary bronchoscopic video. Assuming a two-stage approach for pulmonary disorder

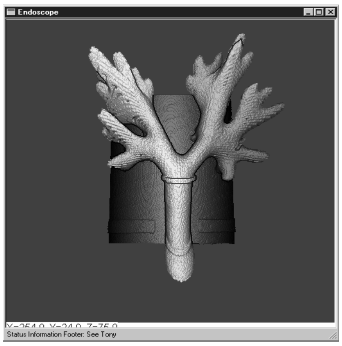
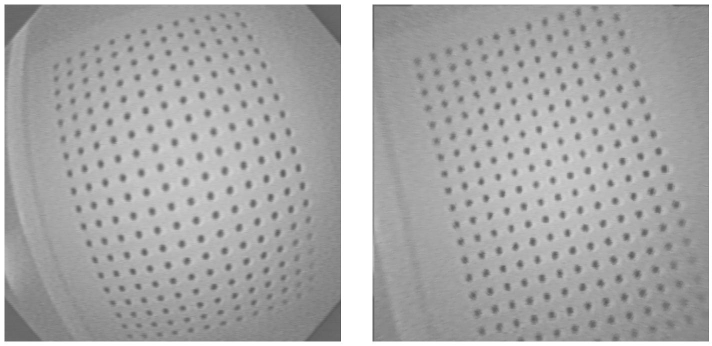


**Figure 7.** Rendering 3D CT image of rubber training device. High-resolution CT data and bronchoscopic video was collected for this device in our CT-video tests.



(a) (b)

**Figure 8.** Example of bronchoscopic video correction.[37] The bronchoscope first images a test pattern. A correction transformation is then computed from this pattern. For subsequent CT-video matching, the corrected video is used. Results shown: (a) distorted bronchoscopic video image of a test pattern; (b) corrected video image.

assessment, we demonstrated the potential of complete case-study construction, assisted by automated analysis and visualization tools, for patient assessment. Not only is this analysis applicable to CT assessment, but it can also supplement real-time bronchoscopy, a major benefit.

The demonstrated approach is currently undergoing validation studies. We hope to determine effective protocols for lymph-node analysis, thick-wall detection, pathology follow-up, and stent design. At this time, the proper sequence of operations and cadre of tools needed is unknown for such protocols. In the long run, we believe such tools will give a more effective means for the early detection, staging, diagnosis, and treatment of lung cancer than the traditional approach. Such tools also could prove useful for general pulmonary disease assessment and treatment.

## ACKNOWLEDGMENTS

This work was partially supported by NIH grants # R01-CA74325 and # R01-RR11800, by the Whitaker Foundation, and by the Olympus Corporation.

## REFERENCES

1. W. E. Higgins, K. Ramaswamy, R. Swift, G. McLennan, and E. A. Hoffman, "Virtual bronchoscopy for 3D pulmonary image assessment: State of the art and future needs," *Radiographics* **18**, pp. 761–778, May-June 1998.
2. D. P. Naidich, J. F. Gruden, G. McGuinness, D. I. McCauley, and M. B. Bhalla, "Volumetric CT (VCT) of the airways," *J. Thoracic Imag.* **12**, pp. 11–28, March 1997.
3. D. J. Vining, R. Y. Shifrin, E. K. Grishaw, K. Liu, and D. W. Gelfand, "Virtual colonoscopy," *Radiol. Scient. Prog.* **193**, p. 446, 1994.
4. W. E. Higgins and K. Ramaswamy, "Toward dynamic visualization for endoscopy simulation," *16th Annual Int. Conf. IEEE Engin. Medicine & Biology Soc.* , pp. 700–701, 3-6 Nov 1994.
5. W. E. Lorensen, F. A. Jolesz, and R. Kikinis, "The exploration of cross-sectional data with a virtual endoscope," *Interactive Technology and the New Health Paradigm* , pp. 221–230, Jan. 1995.
6. A. K. Hara, C. D. Johnson, J. E. Reed, D. A. Ahlquist, H. Nelson, R. L. Ehman, C. M. McCollough, and D. M. Ilstrup, "Detection of colorectal polyps by computed tomographic colography: feasibility of a novel technique," *Gastroenter.* **110**, pp. 284–290, Jan. 1996.
7. D. J. Vining, K. Liu, R. H. Choplin, and E. F. Haponik, "Virtual bronchoscopy: relationships of virtual reality endobronchial simulations to actual bronchoscopic findings," *Chest* **109**, pp. 549–553, Feb. 1996.
8. G. D. Rubin, C. F. Beaulieu, V. Argiro, H. Ringl, A. M. Norbash, J. F. Feller, M. D. Dake, S. Napel, R. B. Jeffrey, and S. Napel, "Perspective volume rendering of CT and MR images: applications for endoscopic imaging," *Radiology* **199**, pp. 321–330, May 1996.
9. R. M. Summers, D. H. Feng, S. M. Holland, M. C. Sneller, and J. H. Shelhamer, "Virtual bronchoscopy: Segmentation method for real-time display," *Radiology* **200**(3), pp. 857–862, Sept. 1996.
10. R. M. Summers, "Navigational aids for real-time virtual bronchoscopy," *Am. J. Roentgen.* **168**, pp. 1165–1170, May 1997.
11. R. M. Summers, "Image gallery: a tool for rapid endobronchial lesion detection and display using virtual bronchoscopy," *J. Digital Imaging* **11**, pp. 53–55, August 1998.
12. K. H. Englmeier, M. Haubner, C. Kraplicher, D. Schuhmann, M. Seemann, H. Furst, and M. Reiser, "Virtual bronchoscopy based on spiral-CT images," *SPIE Medical Imaging '98: Image Display* **3335**, pp. 427–438, 1999.
13. K. Mori, Y. Suenaga, J. Toriwaki, J. Hasegawa, H. Anno, K. Katada, and H. Natori, "Automated display of anatomical name of bronchial branches in virtual bronchoscopy system and its application as a training tool for medical students," *SPIE Medical Imaging '99: Physiol. and Func. from Multidim. Images* **C.T. Chen and A.V. Clough (ed.), v. 3660**, pp. 301–312, 1999.
14. D. J. Vining, D. R. Stelts, D. K. Ahn, and Y. Ge, "New paradigm for virtual colonoscopy processing and reporting," *Radiology* **213(P)**, p. 577, Nov. 1999.

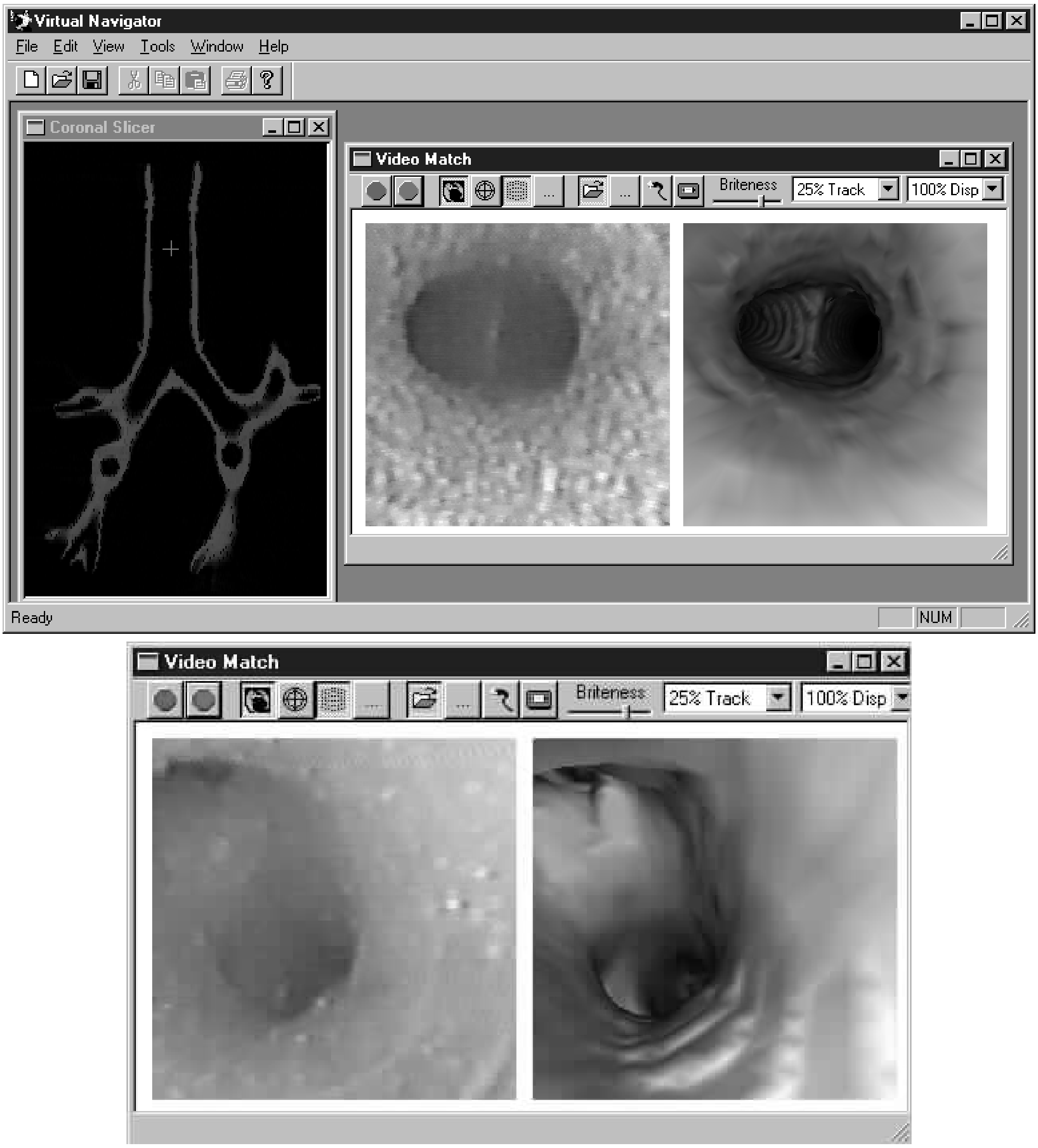



**Figure 9.** Examples of the *Video Match* tool. Top part is near the carina of the bronchoscopy training device. A surface-rendered endoluminal view is calculated and displayed that matches the live bronchoscopic video. A mutual-information optimization algorithm is run that adjusts the virtual system's viewpoint in the rendered CT to match the video viewpoint. The global position of this viewing site is indicated by the "+" in the *Coronal Slicer* view (a cross-section through the original 3D CT scan of the model). Bottom part of figure is at the second bifurcation point of the model. This image shows how a best match of the rendered CT to the video frame is done by weighting the dark values more than the light values. In both images the lighter areas contain inconsistent textures.

15. E. F. Haponik, S. L. Aquino, and D. J. Vining, "Virtual bronchoscopy," *Clinics in Chest Med.* **20**, pp. 201–217, March 1999.
16. T. Fleiter, E. M. Merkle, A. J. Aschoff, G. Lang, M. Stein, J. Gorich, F. Liewald, N. Rilinger, and R. Sokiranski, "Comparison of real-time virtual and fiberoptic bronchoscopy in patients with bronchial carcinoma: opportunities and limitations," *Am. J. Roentgen.* **169**, pp. 1591–1595, Dec 1997.
17. I. Bricault, G. Ferretti, and P. Cinquin, "Registration of real and CT-derived virtual bronchoscopic images to assist transbronchial biopsy," **17**, pp. 703–714, Oct. 1998.
18. H. P. McAdams, P. C. Goodman, and P. Kussin, "Virtual bronchoscopy for directing transbronchial needle aspiration of hilar and mediastinal lymph nodes: a pilot study," *Am. J. Roentgen.* **170**, pp. 1361–1364, May 1998.
19. W. E. Higgins, A. J. Sherbondy, J. P. Helferty, A. P. Kiraly, G. McLennan, and E. A. Hoffman, "Pc-based system for automated quantitative virtual bronchoscopy," *Radiology* **213(P)**, p. 495, Nov. 1999.
20. K. Fujimura, Y. Fujino, T. Matsumoto, T. Uruma, A. Furukawa, and K. Nagao, "Network-based reading system for a lung cancer screening CT," *Radiology* **213(P)**, p. 578, Nov. 1999.
21. K. Ramaswamy and W. E. Higgins, "Interactive dynamic navigation for virtual endoscopy," *Computers in Biology and Medicine* **29**, pp. 303–331, Sept.-Oct. 1999.
22. W. Schroeder, K. Martin, and B. Lorensen, *The Visualization Toolkit, 2nd. Ed.*, Prentice-Hall PTR, Upper Saddle River, NJ, 1998.
23. J. Z. Turlington and W. E. Higgins, "Improved techniques for sliding-thin slab volume visualization," *SPIE Medical Imaging 2000: Image Display* **3976**, S K Mun, ed., 2000.
24. M. Fowler and K. Scott, *UML Distilled*, Addison Wesley Longman, Inc., Reading, MA, 1997.
25. *Rational Rose 98, Using Rational Rose*, Rational Software Corporation, Cupertino, CA, 1998.
26. F. A. Jolecz, W. E. Lorensen, H. Shinmoto, H. Atsumi, S. Nakajima, P. Kavanaugh, P. Saiviroonporn, S. E. Seltzer, S. G. Silverman, M. Philips, and R. Kikinis, "Interactive virtual endoscopy," *Am. J. Roentgen.* **169**, pp. 1229–1235, Nov. 1997.
27. K. Ramaswamy and W. E. Higgins, "Endoscopic exploration and measurement in 3D radiological images," in *SPIE Medical Imaging 1996: Image Processing*, vol. 2710, pp. 511–523, (Newport Beach,CA), 10-15 Feb. 1996.
28. D. S. Paik, C. F. Beaulieu, R. B. Jeffrey, G. D. Rubin, and S. Napel, "Automated flight path planning for virtual endoscopy," *Med. Phys.* **25**, pp. 629–637, May 1998.
29. Y. Ge, D. J. Vining, D. K. Ahn, and D. R. Stelts, "Colorectal cancer screening with virtual colonoscopy," *SPIE Medical Imaging '99: Physiol. and Func. from Multidim. Images,* **C.T. Chen and A.V. Clough (ed.), v. 3660**, pp. 94–105, 1999.
30. A. Austin, "Automatic analysis methods for virtual endoscopic assessment," Master's thesis, The Pennsylvania State University, 2000.
31. R. D. Swift, W. E. Higgins, E. A. Hoffman, G. McLennan, and J. M. Reinhardt, "Automatic axis generation for 3D virtual-bronchoscopic image assessment," *SPIE Medical Imaging 1998: Physiology and Function from Multidimensional Images* **3337**, pp. 73–84, E.A. Hoffman (ed.), 1998.
32. G. McLennan, E. A. Hoffman, R. Swift, and W. Higgins, "Virtual bronchoscopic assessment of major-airway obstructions," *SPIE Medical Imaging 1999: Physiology and Function from Multidimensional Images* **3660**, pp. 313–320, A. Clough and C.T. Chen, eds., 1999.
33. K. Wang, "Staging of bronchogenic carcinoma by bronchoscopy," *Chest* **106**, pp. 588–593, Aug. 1994.
34. H. Minami, Y. Ando, F. Nomura, S. Sakai, and K. Shimokata, "Interbronchoscopist variability in the diagnosis of lung cancer by flexible bronchoscopy," *Chest* **105**, pp. 1658–1662, June 1994.
35. M. L. Brady, K. Ramaswamy, R. Srinivasan, and W. E. Higgins, "Dynamic template-based method for 3D virtual-endoscopic exploration," *Optical Engineering* **38**, pp. 2162–2175, Dec. 1999.
36. K. V. Asari, S. Kumar, and D. Radhakrishnan, "A new approach for nonlinear distortion correction in endoscopic images based on least squares estimation," *IEEE Transactions on Medical Imaging* **18**, pp. 345–354, April 1999.
37. C. Zhang, J. P. Helferty, G. McLennan, and W. E. Higgins, "Nonlinear distortion correction in endoscopic video images," *submitted to IEEE ICIP-2000* , Sept 10-13 2000.
38. C. Zhang, J. P. Helferty, G. McLennan, and W. E. Higgins, "New method for nonlinear endoscopic distortion correction," *submitted to IEEE Transactions on Medical Imaging* , 2000.
39. N. Hata, W. M. Wells III, M. Halle, S. Nakajima, P. Viola, R. Kikinis, and F. A. Jolesz, "Image guided microscopic surgery system using mutual-information based registration," in *Lect. Notes in Comp. Sci. vol. 1131*, pp. 317–325, K. H. Hohne and R Kikinis, eds., Springer, Berlin 1996.
40. P. Viola and W. M. Wells III, "Alignment by maximization of mutual information," *Int. Journal of Comp. Vis.* **24**, pp. 137–154, Feb 1997.
41. P. Thevenaz and M. Unser, "An efficient mutual information optimizer for multiresolution image registration," *IEEE ICIP-98* **32**, pp. 833–837, Jan 1998.
42. C. Studholme, D. L. G. Hill, and D. J. Hawkes, "An overlap invariant entropy measure of 3D medical image alignment," *Pattern Recognition* **32**, pp. 71–86, Jan 1999.