

Image-Based Reporting for Bronchoscopy

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Bronchoscopy is often performed for staging lung cancer. The recent development of multidetector computed tomography (MDCT) scanners and ultrathin bronchoscopes now enable the bronchoscopic biopsy and treatment of peripheral diagnostic regions of interest (ROIs). Because these ROIs are often located several generations within the airway tree, careful planning and interpretation of the bronchoscopic route is required prior to a procedure. The current practice for planning bronchoscopic procedures, however, is difficult, error prone, and time consuming. To alleviate these issues, we propose a method for producing and previewing reports for bronchoscopic procedures using patient-specific MDCT chest scans. The reports provide quantitative data about the bronchoscopic routes and both static and dynamic previews of the proper airway route. The previews consist of virtual bronchoscopic endoluminal renderings along the route and three-dimensional cues for a final biopsy site. The reports require little storage space and computational resources, enabling physicians to view the reports on a portable tablet PC. To evaluate the efficacy of the reporting system, we have generated reports for 22 patients in a human lung cancer patient pilot study. For 17 of these patients, we used the reports in conjunction with live image-based bronchoscopic guidance to direct physicians to central chest and peripheral ROIs for subsequent diagnostic evaluation. Our experience shows that the tool enabled useful procedure preview and an effective means for planning strategy prior to a live bronchoscopy.

KEY WORDS: Image-based reporting, image-guided surgery, 3D imaging, virtual bronchoscopy, lung cancer, bronchoscopy

INTRODUCTION

Lung cancer staging often begins with the acquisition and analysis of a three-dimensional (3D) multidetector computed tomography (MDCT) chest scan. If a pathologically suspicious region of interest (ROI) is found during the assessment of the 3D MDCT image, a follow-on bronchoscopy may be performed¹⁻⁵. During the follow-on procedure, the physician inserts a flexible bronchoscope into the patient's airways,

navigates to an appropriate location in the airway tree, and then uses bronchoscopic accessories, such as a needle or forceps, to sample the ROI.

In practice, ROIs may be solitary pulmonary nodules or diffuse masses situated several airway generations beyond the trachea. Often, the ROIs are located outside the airway tree, making direct visual inspection impossible^{2,6}. Without visual feedback, physicians are often forced to blindly perform bronchoscopic biopsies⁴⁻⁷. Because of these difficulties, researchers have documented the significant variation in bronchoscopist skill^{8,9}. These factors conspire to make it difficult to accurately perform peripheral bronchoscopic procedures^{10,11}.

The current practice for planning bronchoscopic procedures requires the physician to scroll through two-dimensional (2D) axial slices of the MDCT image and perform 3D mental reconstruction to determine the appropriate route to reach an ROI. Mentally, defining a route to reach these peripheral ROIs is generally highly error prone^{6,7,10,11}. While there is conflicting data on the rate of malignancy of peripheral ROIs, successfully sampling such lesions could be beneficial, as some patients could then forego more invasive surgery².

Recent research has shown that biopsy of peripheral lesions using ultrathin bronchoscopes is feasible, given appropriate procedure planning and

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a useful presentation of the route to an ROI¹²⁻¹⁴. In the work of Shinagawa et al., a physician manually determined appropriate airway routes to peripheral ROIs and generated virtual bronchoscopic (VB) depictions of the tracheobronchial tree at informative locations along the routes^{13,14}. Because manually defining and generating appropriate previews of the routes to peripheral ROIs is time consuming for the physician, Shinagawa et al. suggested the need for automation¹³. Asano et al. have recently presented a rudimentary automated approach for bronchoscopic procedure planning¹². Likewise, to address the difficulties in bronchoscopic planning, we have developed an integrated planning system^{15,16}. Nearly all components of our system are automatic, requiring only limited physician interaction to plan a procedure for a selected ROI. In this paper, we present a reporting system that generates bronchoscopic reports from our system's output planning data.

Our automated reporting system generates two types of outputs from the planning data: (1) a static report, presenting relevant visual and quantitative data along the route, and (2) a dynamic report, providing an interactive virtual-reality movie preview of the procedure. The reports allow a physician to preview and gain knowledge of the nuances of a specific case prior to live bronchoscopy and are also useful for archival purposes.

Both the static and dynamic reports can be previewed using a standard web browser (e.g., Internet Explorer or Firefox). Such an interface is beneficial in that most individuals are familiar with how to navigate web pages. Furthermore, web browsers can convey both static and dynamic content with limited storage and processing overhead. Together, these features allow physicians having limited computer experience to preview procedures on almost any computer in the hospital, as no special hardware is necessary.

METHODS

In this section, we first describe the planning input to the report-generation system. Next, we describe the Report Tool, which generates the reports and provides a graphical user interface for selecting report generation options. Lastly, we describe the form of the static and dynamic bronchoscopic reports.

Procedure Planning

Given a patient's 3D MDCT chest image, the procedure-planning process generates the inputs to our reporting system in five main steps¹⁶: (1) define an ROI, (2) segment the airway tree, (3) define the interior surfaces of the tracheobronchial (airway) tree, (4) extract the medial axes (centerlines) of the airways, and (5) determine an appropriate route to the ROI. As each of the planning components have been validated on a wide variety of patients and across a range of images generated by numerous MDCT scanners, we direct the reader to the appropriate publications, which give complete detail on this planning process¹⁶. Below, we summarize the five-step planning process.

Step 1: ROI Definition

The first step of the planning process is to define the target to reach during bronchoscopy. The planning system takes as input a 3D MDCT image and the general location (usually an approximate center of mass) of each ROI. The physician typically notes these locations during the initial examination of the MDCT data. Because ROIs vary greatly in shape and radiologic appearance, a trained technician uses a semiautomated approach to define the set of ROI voxels in the MDCT image at the locations specified by the physician. To minimize the time and effort required by the technician, we utilize the 3D livewire method of Lu and Higgins to segment the ROI (Fig. 1a)¹⁷. This rapid robust method requires the technician to outline the ROI on only a few axial slices. From these cues, a filled ROI volume is then generated.

Step 2: Airway-Tree Segmentation

Effective bronchoscopic procedure planning requires an accurate 3D airway tree, at least along the route leading to the ROI. An airway-tree segmentation, consisting of the set of airway lumen voxels in the MDCT image, is generated by the system of Graham et al. (Fig. 1b)¹⁸. This system automatically extracts the vast majority of the lumen voxels within 2 to 4 min, generally producing segmentations containing hundreds of airway branches. Airway-tree segmentation is part of the procedure planning time broken out in Table 2, as discussed in the "Results". Gibbs et

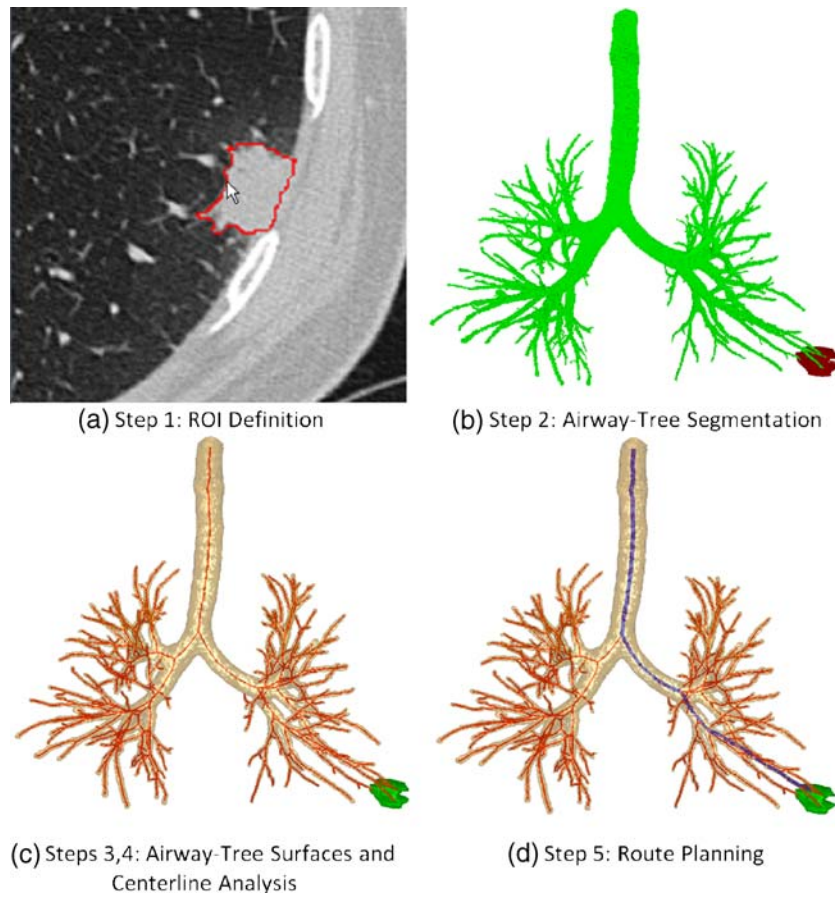


Fig 1. Illustrative inputs from the planning system used to create the bronchoscopic reports¹⁶. For this example, a Siemens Sensation 40 scanner generated the 3D MDCT image (image size: $512 \times 512 \times 654$; voxel resolution $\Delta x = \Delta y = 0.69$ mm, $\Delta z = 0.50$ mm; patient 20349.3.33). a Step 1 (*ROI Definition*): live wire defines a nodule identified by a physician. b Step 2 (*Airway-Tree Segmentation*): segmented airway tree (green) and peripheral lesion (red). c Steps 3, 4 (*Airway-Tree Surfaces and Centerline Analysis*): the airway tree surfaces (tan) and airway centerlines (red) now appear with the peripheral lesion (green). d Step 5 (*Route Planning*): the route to the ROI is now identified (blue). 103×109 mm (300×300 DPI).

al.¹⁶ and Graham et al.¹⁸ point out in greater detail that the segmentation time depends on the quality of the airway tree depicted in the MDCT scan. Because the airways diverging from the route to the ROI provide important visual landmarks that need be represented in the reports, the segmentation system also includes semiautomatic tools for the addition of weakly defined peripheral airways along specific ROI routes.

Step 3: Airway-Surface Definition

From the airway-tree segmentation and MDCT image data, we next define polygonal airway-wall surfaces (Fig. 1c). These surfaces are used to generate the VB renderings in our reports. As such, the overall goal of the surface-definition

strategy is for the resulting VB renderings to accurately reflect the appearance of the airways in the bronchoscopic video feed. We utilize the method of Gibbs et al. to define the surfaces¹⁶. This approach employs the MDCT chest scan in conjunction with the airway-tree segmentation to produce well-defined surfaces for the entire extent of the airway tree.

Step 4: Centerline Analysis

Using the surfaces derived in the previous step, the centerline analysis method of Yu et al. extracts the central axes of the airway tree (Fig. 1c)^{19,20}. These centerlines define virtual bronchoscopic trajectories through the polygonal airway surfaces

and provide potential biopsy locations for the route-planning system. Quantitative measurements, such as airway cross-sectional area and diameters, are associated with airway-centerline locations²¹. These measurements are used in procedure planning and are directly conveyed to the physician in the reports generated by our system.

Step 5: Route Planning

With (1) a definition of the target ROI, (2) the restricted 3D region through which we can navigate to reach the ROI (the polygonal airway surfaces), and (3) estimates of the bronchoscope pose at various locations within the airway tree (the centerlines), the planning system next computes an appropriate optimal route to the ROI. We use the method of Gibbs and Higgins to automatically compute this route (Fig. 1d)¹⁵. This method's computations account for the geometry of both the bronchoscope and the airway tree to help ensure that the bronchoscope can fit along the entire route. The biopsy site is chosen so that the relative geometry between the bronchoscope and the ROI is suitable for the bronchoscopic procedure to be performed. As discussed later, the reports are tailored to show the physician how to reach this precomputed route destination.

Report Tool

The Report Tool constitutes a part of a larger software suite, referred to as the Virtual Navigator System (VNS) we have devised for the planning and guidance of bronchoscopy^{4,5,22}. VNS has been developed for the inspection of MDCT chest scans, incorporating the previously described bronchoscopic planning data for the visualization and follow-on live guidance of bronchoscopic procedures. VNS includes a variety of visualization tools, which allow a user to examine MDCT slices, 3D global and endoluminal renderings of the airway tree and ROIs, and quantitative plots of airway measurements. Appropriate storage, processing, and display requires only a typical desktop workstation and graphics processing unit. Operating within the VNS software suite, the Report Tool creates content that can be viewed on modest laptops or tablet computers with limited processing and graphics-rendering capabilities.

Furthermore, the reports generated by the system require only a few megabytes of storage, enabling practical transfer to and storage on mobile computers. We next provide technical detail on the automatic report generator.

The Report Tool provides a user-friendly interface, as depicted in Figure 2. Creating a report is as simple as invoking the tool, selecting a target ROI, and pressing the "Generate" button. The tool then uses the precomputed planning data to automatically create the HTML and Windows Media Video (wmv) files, constituting the dynamic and static reports.

The tool contains a number of options for fine-tuning reports. For example, the planning data may provide multiple viable routes to an ROI. For such situations, the report generator includes a table summarizing the details of all reasonable routes to each ROI. The ROIs in the report generator table are color-coded and assigned descriptive names to avoid confusion. Information included in the table for each potential route is the ROI principal axes lengths, the airway generation in which the route terminates, the length of the route to the ROI, and the minimum airway diameter encountered along the route.

To further aid in appropriate route selection, the tool includes a virtual bronchoscopic preview window. The preview window allows the user to freely navigate along each possible route. During this virtual navigation, relevant quantitative data such as the airway measurements and the remaining distance to be traversed along the route provide additional perception of a candidate route. Furthermore, visualization tools within the larger VNS system can be invoked and operate in synchrony with the Report Tool's previewer. For example, in Figure 3, the 2D MDCT transverse slice and the orange position indicator within the global airway tree match the location and orientation of the virtual bronchoscopic camera. By previewing the entire route in this multimedia setting, the user can examine stenosed locations, difficult turns, and other practical difficulties. Thus, selection of the final route from among those suggested by the planning component can be made using considerable information. After examining the routes, the user selects the most appropriate path to each ROI for final report generation.

While the automatically created reports are typically sufficient for visualization of the bronchoscopic routes, a number of parameters allow for

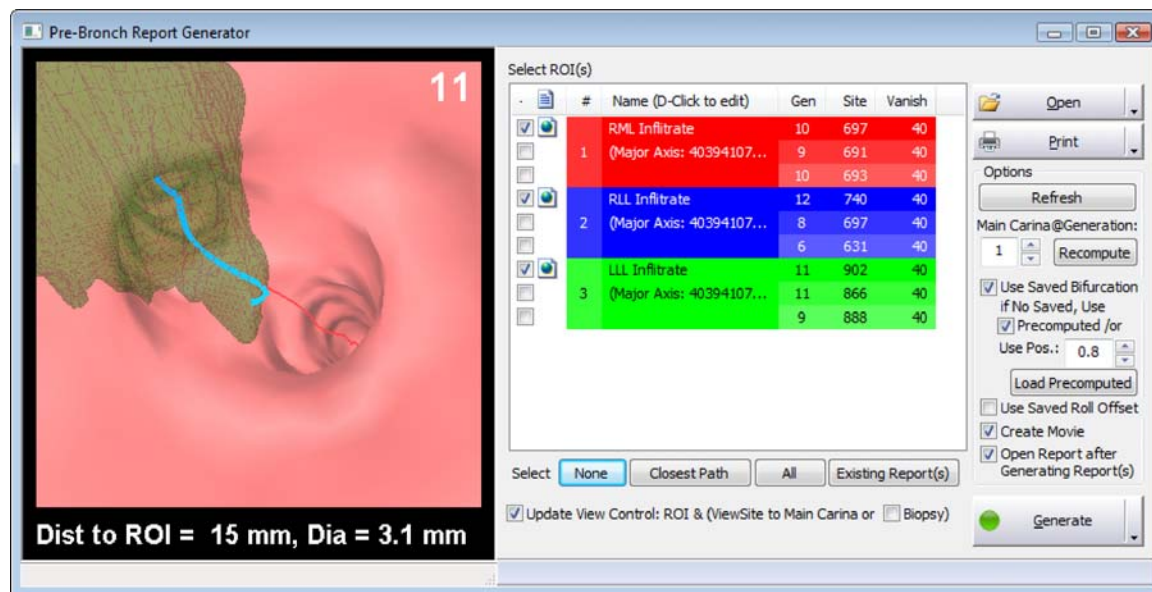


Fig 2. The Report Tool. To create a report, the user determines the precomputed routes to use in the “Select ROI(s)” section. The background color of each ROI in the table corresponds to the color of the ROI in the VB and global airway renderings. The VB rendering, to the left of the ROI table, displays the movie created by the report generator, allowing the user to ensure that correct routes were chosen. The remainder of the interface contains various options, including the generation offset, ROI vanish distance, and variables controlling the location of the key frames in the static report. 74×38 mm (300×300 DPI).

refining the outputs. In some cases, seeing the ROI early along the route in the VB views is reassuring as images of the ROI relative to the endoluminal renderings can provide the physician with a better mental impression of the route. In other cases, premature display of the ROI can distract the viewer from understanding bifurcation structures. To address these issues, a “vanish distance,” which specifies how the ROI is blended into the VB views, can be tweaked at the physician’s preference. Reports with large vanish distances blend the ROI into the VB views before those with small vanish distances.

The tool also provides some flexibility in the definition of the branch generation numbers used in the report. This is useful, for example, if a patient’s lungs contain the anatomical variation known as “bronchus suis”, or “prearterial bronchus”, where an extra bronchus extends from the trachea²³. In this case, the main carina will occur at the end of a second-generation airway and the remaining generation numbers will become nonstandard. To avoid confusion, the generation number of the main carina can be set as an option. The generation numbers of the remaining airways are adjusted appropriately to correlate with standard anatomy.

Upon selecting the appropriate routes and parameters, the HTML and wmv content are generated automatically by the Report Tool. The following discussion details the one-page static and dynamic movie-preview outputs.

Static Report

The static report presents the salient features of an entire bronchoscopic route on a single printed page (Fig. 4). This report allows the physician to gain a mental impression of the route prior to bronchoscopy. In addition to displaying the patient’s anatomy in a more intuitive manner than observation of the 2D MDCT slices, a static report provides the physician with visual and quantitative cues similar to that available in the preview tool, data that are unavailable in standard bronchoscopy. For example, the route from the trachea to the final suggested biopsy site is highlighted in blue, providing an unambiguous path for the physician to follow during live bronchoscopy. At the route destination, a 4-mm-long arrow indicates the biopsy site, pointing toward the ROI. While the ROI may be located extraluminally and therefore out of sight in the bronchoscopic video feed during

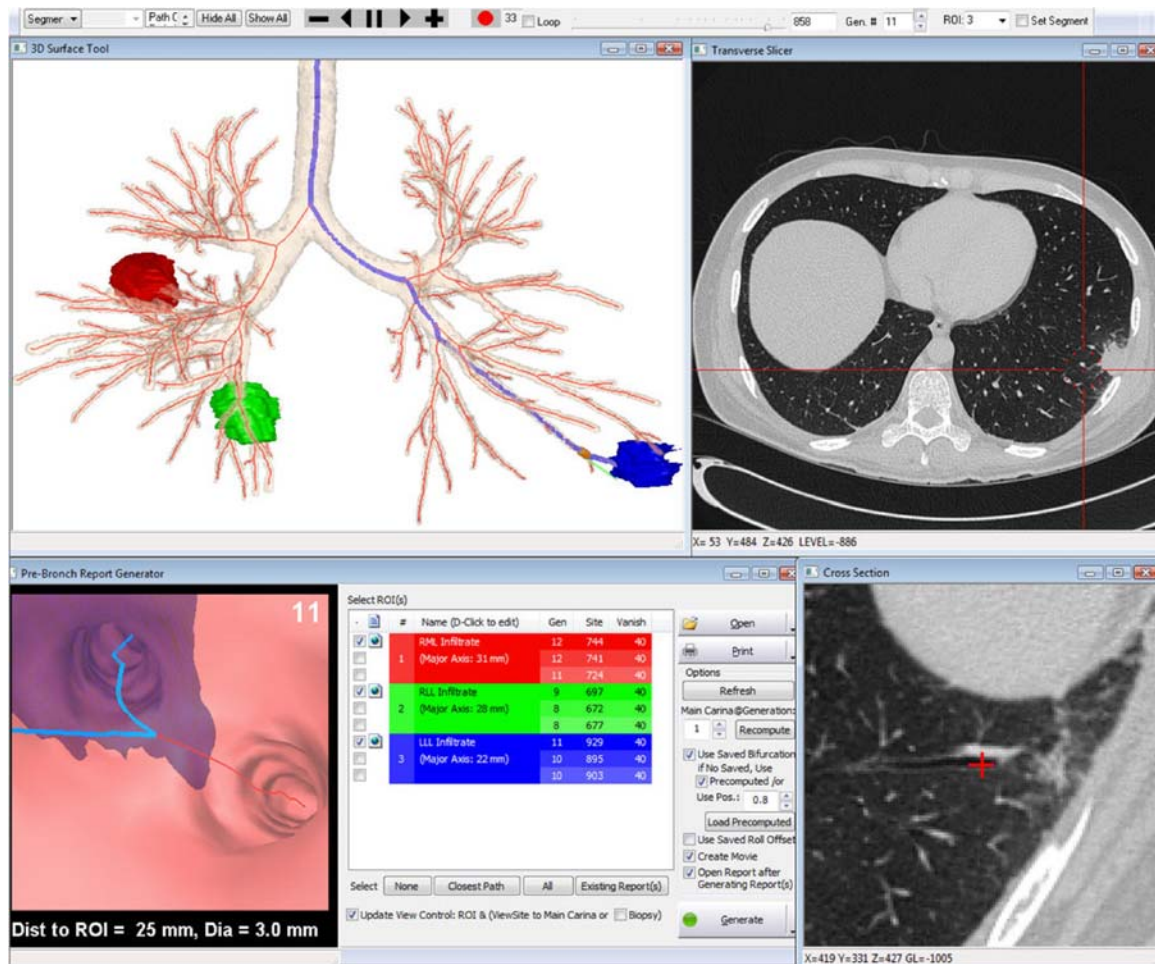
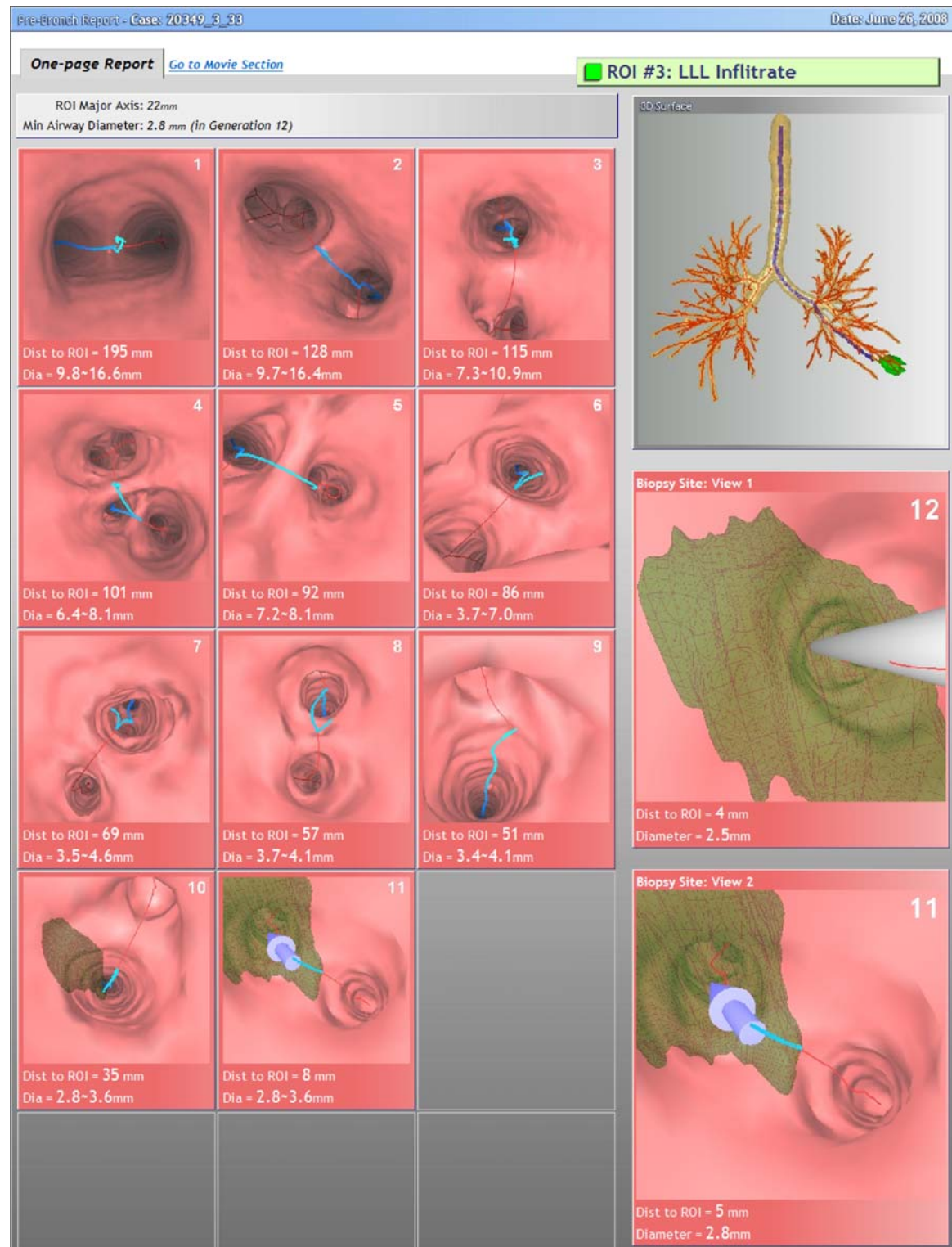


Fig 3. Integrated views of the Virtual Navigator System software suite^{4,5,22}. The 3D Surface Tool (top left) provides a global view of the airway tree, centerlines (red), ROIs (red, green, and blue), and the route to a particular ROI (blue). The arrow highlights the position of the virtual bronchoscope in the airway tree. The position of the virtual bronchoscope is also displayed in a transverse MDCT slice (top right). The left lower lobe infiltrate (green ROI in the 3D surface tool) is circled in the MDCT slice. The report preview tool (bottom left) provides an endoluminal view of the 11th generation airway and ROI at the same location as the other views. The ROI, which is located beyond the airway walls, is blended in to the scene to convey its location to the physician. An oblique cross-sectional MDCT section (bottom right) shows a local view of the airway and upcoming lesion. The red cross indicates the current virtual bronchoscopic position. As the user previews the route, each of these views dynamically update in synchrony. The dimensions of the MDCT data are 512×512×654 with $\Delta x = \Delta y = 0.69$ mm and $\Delta z = 0.50$ mm (case 20349.3.33). 92×76 mm (300×300 DPI).

the procedure, the ROI is blended into the endoluminal renderings, giving the physician a sense of the ROI's 3D location.

The numbered VB renderings to the left of the report provide a view for each bifurcation encountered along the route leading to the ROI. The location of the virtual bronchoscopic "camera" used to capture each of these bifurcations is automatically computed using a previously proposed method²⁴. The VB views are enhanced with airway centerlines and the preselected route to the ROI is represented by a thick blue line. The ROI is

Fig 4. Example static report. The Report Tool automatically generates this report, providing relevant quantitative data about the ROI and the defined 3D bronchoscopic route. A global view (upper right) shows the airway tree, the suggested route (blue) and the ROI (green). The VB renderings depict endoluminal views of each bifurcation encountered along the route (11 total) and at the final suggested biopsy site (two Biopsy Site Views). The 4-mm-long blue arrow indicates the suggested biopsy puncture site in the generation 11 views. The biopsy site view at generation 12 shows a tool extending from the bronchoscope's working channel to sample the ROI. Each view also provides the distance remaining to reach the ROI ("Dist to ROI") and a range of the minimum diameters in each bronchus (case 20349.3.33). 84×110 mm (300×300 DPI).



blended into the views near the route destination, indicated by the blue arrow, which appears at the final suggested biopsy site.

The visual cues are supplemented with quantitative data. The airway generation number is superimposed in the upper-right corner of the renderings, informing the physician of the depth of the virtual bronchoscope within the patient's anatomy. Related to this, the "Dist to ROI" label informs the physician of the remaining distance along the route. Each frame of the static report also provides the range of cross-sectional airway diameters for the airway branch.

Three additional renderings appear to the right of the static report. The top view provides a global 3D view illustrating the surfaces of the entire airway tree and the target ROI. The middle rendering depicts the biopsy site from the perspective of the bronchoscope, with the diagnostic tool extending from the bronchoscope's working channel. Ideally, the ROI should fill the entire view, implying the physician need not precisely align the bronchoscope to sample the ROI. The bottom view shows the ROI and the arrow indicating the biopsy site from a point near the end of the route.

The report also provides global information on the ROI and route. This information includes the total number of airway generations and the narrowest airway diameter encountered along the route to the ROI. Due to the perspective projections used to create the VB movie, the true size of the ROI cannot be easily determined in the dynamic movie. For example, a large ROI located some distance from the biopsy location can appear similar to a small ROI located just beyond the airway wall. The diameter of the major axis of the ROI, provided at the top of the report, helps the physician disambiguate the visual information in the report.

Dynamic Report

Figure 5 shows use of a dynamic report on a portable tablet PC. The dynamic report consists of an interactive movie player, which displays the virtual-reality procedure-preview content, and play-back controls, which allow the physician to interact with the preview movie (Fig. 6). The preview movie allows the physician to visualize the route in a even more realistic manner than the static reports. Instead of discrete views before each bifurcation, the preview movie shows the entire

route in a manner similar to the live bronchoscopic video feed. In addition, past medical visualization research shows that dynamic animations reveal more information and give a fuller impression of the underlying 3D anatomy than static single-frame views^{25,26}.

Various controls allow the physician to interact with the movie. Basic navigation features such as play forward, slow-speed, normal-speed, and fast-speed play control the movie, much like a DVD player. For fine control, the physician can also step forward or backward a frame (or many frames) at a time. Alternatively, the physician can jump directly to particular airway-tree generation by selecting the appropriate bifurcation in the "Click to jump" section. With the flexibility provided by the dynamic reports, the physician can preview anatomically interesting or challenging portions of the route. As such, the dynamic reports allow for a better mental impression of the bronchoscopic procedure than can be achieved through inspection of the raw MDCT data.

RESULTS

The Report Tool has been used extensively in an on-going peripheral bronchoscopic live human



Fig 5. Previewing a dynamic report on a tablet PC. The physician reviews a case on the portable computer prior to live bronchoscopy. 68×73 mm (300×300 DPI).

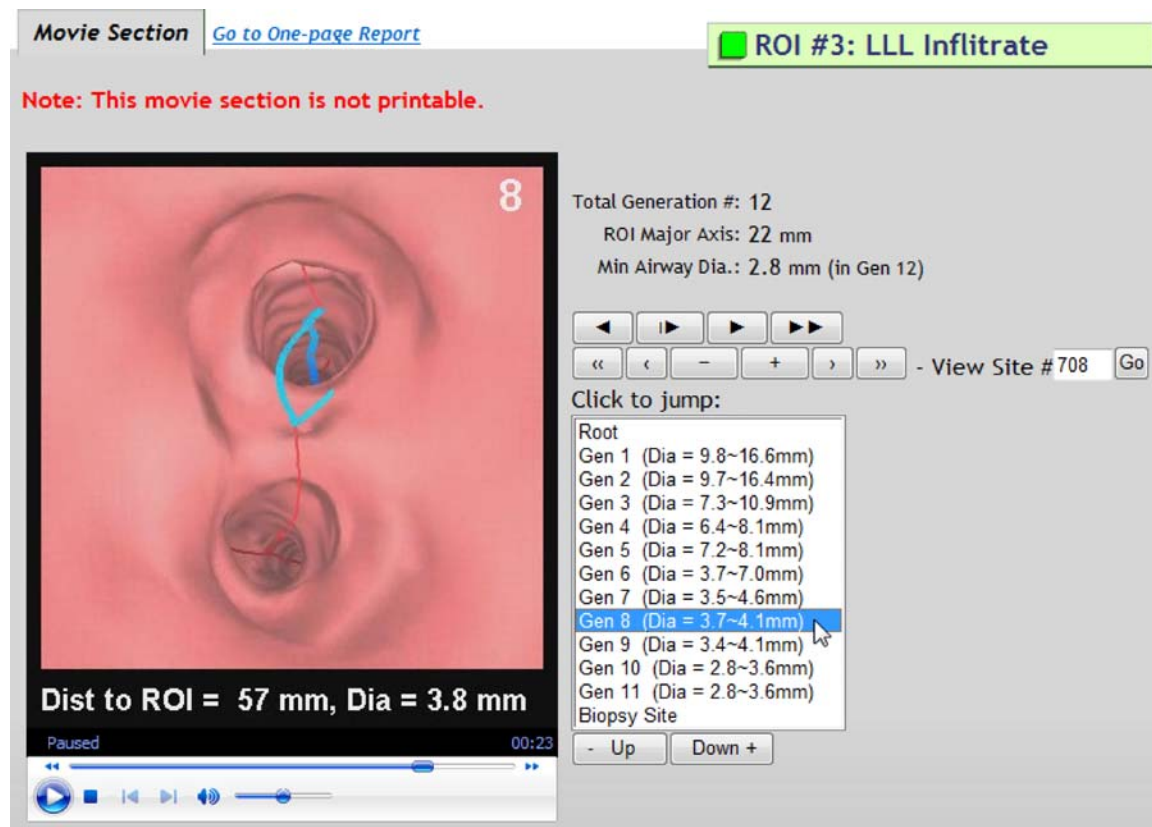


Fig 6. The dynamic report. The left pane shows the VB preview movie with the superimposed generation, minimum-diameter, and distance-to-ROI information. The right-half portion of the figure shows the various movie controls that allow the physician to interact with the VB movie (case 20349.3.33). 66×47 mm (300×300 DPI).

study, approved by our University's institutional review board²⁷. We drew upon 3D MDCT image data from a variety of Siemens MDCT scanners (Sensation-16, Sensation-40, and Sensation-64 models) and one case from a Philips True Flight Gemini PET-CT scanner (the CT scanner had 16 detectors). The general parameters for the MDCT scans abided by a submillimeter pulmonary scanning and reconstruction protocol at our institution as follows: slice thickness=0.75 mm, slice spacing $\Delta z=0.50$ mm; transverse-plane resolution ($\Delta x=\Delta y$) between 0.50 and 0.86 mm; smooth and/or sharp reconstruction kernels used.

To date, we have generated reports for 22 cases containing a total of 72 suspect peripheral ROIs (Table 1). Of the cases considered, live procedures were performed for 17 patients to a total of 37 ROIs²⁷. Two university staff pulmonologists and assisting pulmonary fellows in training employed the Report Tool for previewing a case and

planning strategy for a potential subsequent live bronchoscopy. In addition, the physician also always conferred with an assisting lab technician to plan strategy for the live procedure. Later, during the live procedure, the physician and technician, who operated the VNS guidance system, worked in synchrony.

Table 2 summarizes the computation times for five of the peripheral cases examined in the study. This table provides the execution time required for generating the automatic planning data and the static and dynamic reports, excluding the time required for file I/O. The calculations were performed on a standard dual-core 2.6-GHz, 4-GB RAM Windows XP PC. To compute the planning times, we include the time required for human interaction with the planning system¹⁶, e.g., defining the ROIs and verifying the appropriateness of the airway model. For cases with multiple ROIs, the times are averaged to find the time

Table 1. Summary of Human Lung Cancer Cases Used in an Ongoing Study (IRB protocol 20349.3)²⁷

Case	# Reported ROIs	# Guided ROIs	Median generation # (min–max)
23	5	–	9 (7–12)
24	1	1	13
25	1	1	8
26	2	2	8 (8–8)
27	1	–	8
28	1	1	9
29	2	2	9 (5–13)
30	1	1	11
31	8	–	10 (7–13)
32	1	–	8
33	3	3	12 (10–13)
34	5	2	10 (7–12)
35	3	3	7 (7–7)
37	4	2	6 (5–7)
38	6	3	9 (7–13)
39	4	2	6 (2–7)
40	4	3	7.5 (4–11)
41	3	3	13 (8–14)
42	2	2	9 (9–9)
44	10	4	8.5 (8–12)
45	5	2	10 (1–12)

“# Reported ROIs” is the number of ROIs identified for planning and reporting in the case. For those cases in which a live bronchoscopic procedure was performed using the reports, “# guided ROIs” indicates the number of ROIs the physician attempted to sample. The rightmost column provides the median airway-tree generation of the ROIs for which reports were generated (trachea = generation 1). For cases with multiple ROIs, the “min” and “max” values give a range of the depths of the reported bronchoscopic routes

required for a typical case consisting of a single ROI target. The reports are generated very quickly, requiring well under a minute of processing time in all cases. The short execution times of both the planning and report generation systems fit well

within the clinical workflow. In our studies, a technician performed all operations in the procedure planning phase, except for selecting the locations of the ROIs (beginning of step 1 in the procedure-planning process). Note that the physician performs this operation in standard practice, regardless of the availability of the VNS system; hence, this step does not increase their workload. Also, as stated earlier, virtually all other steps in procedure planning are automatic. Finally, it is important to realize that all planning steps, with the exception of selecting/defining the ROIs is done once per case, regardless of the number of ROIs selected. Therefore, the total planning time does not increase linearly with the number of selected ROIs.

Figure 4 shows a static one-page report for a peripheral left-lower-lobe infiltrate. Following this plan, a bronchoscopist was able to sample the infiltrate via bronchoalveolar lavage and cytologic brushing with a Olympus BF-XP160F 2.8-mm ultrathin bronchoscope during the follow-on live procedure²⁷. Each report frame corresponds to a separate bronchus (branch of the airway tree) in the route to the ROI. The VB renderings, numbered by airway generation, are endoluminal views of the polygonal airway surfaces. In each of the frames, the size, shape, and configurations of the visible airways provide the bronchoscopist with the landmarks required to remain oriented throughout the procedure. The range of diameter values alert the physician to those airways where the bronchoscope may fit tightly within the airway tree during the procedure. The green ROI is visible in the final frames (generations 10, 11) and the large “biopsy site” frames on the right.

Table 2. Analysis of the Timing Requirements for Planning and Report Generation

	Case					Mean
	23	24	25	29	30	
# of ROIs	5	1	1	2	2	2.2
Procedure planning (min:s)	11:40	14:36	11:48	21:56	15:07	13:53
Report generation (s)	15	29	16	17	14	16
Total (min:s)	11:55	15:05	12:04	22:13	15:20	14:10

The “# of ROIs” row gives the number of ROI targets identified in each patient. “Planning” indicates the time required for all the steps of “Procedure Planning”, while “report generation” indicates the time required to automatically compute the reports. “Total” provides the overall execution times, omitting the time required for file input/output. Because some cases contain multiple ROIs, the time requirements for planning and creating the reports in the “mean” column are averaged on a per-ROI basis

DISCUSSION

We have described a software tool for computing and previewing reports for peripheral bronchoscopic procedures based on patient-specific 3D MDCT chest scans. The tool takes as input automatically generated planning data, which model the diagnostic ROI, the airway tree, and an appropriate bronchoscopic route, and generates static and dynamic reports as outputs. For a given route, the static report presents virtual bronchoscopic endoluminal renderings at each bifurcation, branch-level quantitative measurements, and other important information on a single printed page. The dynamic report provides an interactive movie that displays a virtual-reality preview of the procedure. Our reports distill complex procedure-planning information derived from a number of automatic and interactive processing algorithms into a small easy-to-understand package. They can be viewed in a standard internet browser using a simple laptop or tablet PC.

A major benefit of the reports is that they can be viewed and stored on facilities with limited computational resources (Fig. 5). The HTML and wmv files in our reports require a small fraction of the storage required for the MDCT and planning data. For example, the total storage requirement for both the static and dynamic reports for the three ROIs of case 20349.3.33 (Figs. 1 and 4) is only 8.3 MB. This is contrasted with the 406 MB of disk space required for the 3D MDCT image and intermediate planning files. In general, the reports typically require $\approx 2\%$ of the storage needed for the MDCT image, centerline, airway surfaces, and related planning data. Note that the compact storage needs of a typical report is not a result of any particular effort to perform data compression. Instead, it occurs simply because a report only consists of information along the few selected airway routes pertaining to the predefined ROIs. These routes represent a tiny fraction of the overall vast anatomical data contained in a typical 3D MDCT chest scan.

We previously conducted a simulation study, whereby 14 pulmonologists with varying levels of experience attempted to plan routes through the airways leading to ROIs situated in peripheral airways¹⁰; the ROIs were located between third- and fifth-generation bronchi. The participants used either standard practice, whereby they could scroll

through high-resolution 3D MDCT chest image data on a computer console, or endoluminal movies akin to our proposed Report Tool. The study showed a path-selection accuracy of $96 \pm 3\%$ using endoluminal views versus $40 \pm 28\%$ using standard practice. A later phantom study comparing standard practice to our VNS system bears out this improvement for live bronchoscopy¹¹. Hence, it seems clear that the Report Tool adds considerably to the planning accuracy of procedures involving peripheral airways.

In fact, all participating pulmonologists enjoyed using the Report Tool in our current human studies. As the presentation of the Report Tool essentially mimics what our VNS system presents during live image-guided bronchoscopy, the Report Tool in reality is an indispensable and integral part of the overall VNS system. The major advantage offered by the report is that it enables the pulmonologist to preview—without time or live-procedure pressure—how the real procedure will proceed before actually doing it. In this way, the pulmonologist can preplan strategy and coordinate maneuvers with the assisting technician prior to the live procedure. We point out that the reports can be previewed off-line before the procedure or during the live procedure before embarking on bronchoscopy of a particular ROI.

The reports generated by our system have been used to preview difficult biopsies of peripheral ROIs located as many as 14 airway-tree generations from the trachea. In general, the system functions robustly as long as the 3D MDCT chest image data has a spatial resolution of 1–2 mm or less. This is in line with the constraint that the major airways of the human tracheobronchial tree approximately range in diameter from 2 (generation 10) to 25 mm (the trachea). Such data ensures sufficient resolution to segment and make satisfactory endoluminal renderings of major airways (those having diameters on the order of 2 to 25 mm).

Finally, while our image-based reporting system is not appropriate for single-axis nonbifurcating structures such as the colon, it could be applicable to anatomical structures made up of bifurcating hierarchical networks, such as the coronary arteries or other vascular networks²⁰. For this domain, all of our methodology, both in “[Procedure Planning](#)” and in the “[Report Tool](#)”, should be directly applicable, with the exception of the image-

segmentation step of procedure planning (step 2). For this step, a suitable vasculature extraction method could be substituted, but we have not verified this conjecture.

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