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Virtual bronchoscopy for evaluation of airway disease☆

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A variety of medial conditions can cause airway stenoses that require intervention by thoracic surgeons. For instance, patients who have primary lung cancers or pulmonary metastases frequently develop complete bronchial obstructions secondary to endoluminal tumors or extrinsic compression [1]. Patients who have a variety of nonmalignant conditions can also develop severe pulmonary complications including fixed tracheobronchial stenoses, tracheomalacia, or hemoptysis [2].

Typically, patients who have suspected airway disease undergo diagnostic evaluation consisting of chest radiographs and conventional CT scans followed by fiberoptic bronchoscopy [3]. Conventional CT generates two-dimensional (2D) cross-sectional images of the thorax, which provide information regarding peribronchial anatomy. Standard CT scans have a sensitivity of 63% to 100% and a specificity of 61% to 99% for detection of major endobronchial disease [4–6]. Occasionally, suboptimal scanning techniques, inappropriate slice thickness, and other artifacts might limit the accuracy of airway anatomy defined by conventional CT scans [7].

In clinical practice, fiberoptic bronchoscopy (FB) remains the gold standard for evaluation and surveillance of endoluminal lesions within the respiratory tract; however, FB yields little information regarding the extent of extraluminal disease or airway patency beyond a high-grade stenosis [8]. In addition, FB might pose potential risks to patients who have advanced pulmonary disease (morbidity 0.8%) because some degree of sedation might be required [9].

Recently, virtual bronchoscopy (also referred to as CT bronchoscopy) has become available for noninvasive evaluation of the tracheobronchial tree [3]. Virtual bronchoscopy (VB) uses three-dimensional (3D) reconstruction of super high-resolution helical CT (SHR-CT) images for delineation of the tracheobronchial tree. Perspective surface or volume rendering of 2D CT scan images are used to construct a virtual airway. The natural contrast between the soft tissue of the airway wall and air within the tracheobronchial tree establishes a plane for generating the virtual airway [6]. The viewer can navigate through the virtual airway in a 3D manner analogous to standard FB. VB also enables imaging of endoluminal and extraluminal anatomy, which is not possible with FB. The virtual airway can be manipulated in space and evaluated from multiple angles (Fig. 1; Movie 1 in online version of this article).

Technique

Two hundred to 300 contiguous images of the thorax are obtained using a multislice helical CT scanner [10]. The standard technique at the National Institutes of Health is 1.25 collimation, helical scan (HS) mode (helical pitch 6; 7.5 mm table motion per

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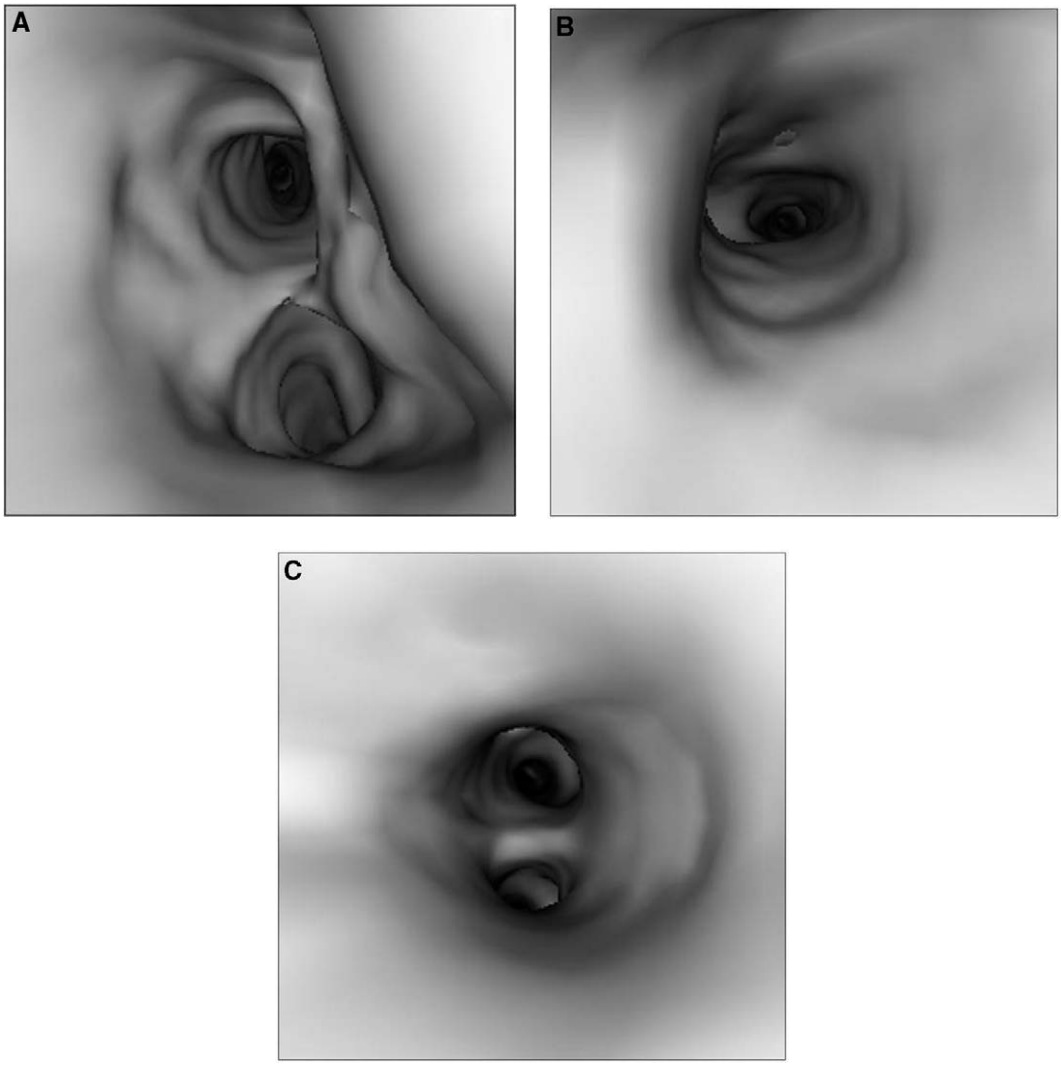

Fig. 1. Virtual bronchoscopy (VB) of normal anatomy. Viewpoint is above carina (*A*), looking into right mainstem bronchus (*B*), a segmental bronchus (*C*). A three-dimensional movie of VB is available in the online version of this article found at doi:10.1016/S1052-3359(03).

rotation, 120 kVp, 100 mAs, 0.8 sec tube rotation, nonoverlapping reconstructions with a section interval of 1.25 mm, and an effective z-axis resolution of ~1.6 mm). A standard algorithm is used to generate the CT images [10]. The radiation dose with this technique is the same or slightly less than that of a conventional thoracic CT scan.

VB images can be viewed as standard CT scans or reconstructed to 3D endoscopic views using commercial software (ie, GE Navigator on a GE Advantage Windows workstation, General Electric, Milwaukee, Wisconsin). The radiologist or surgeon can review the VB in a systemic manner. With the viewpoint placed first in the proximal trachea, retrograde inspection of the subglottis is done. Next, antegrade inspection of the trachea is performed, followed by evaluation of the right mainstem bronchus, right upper lobe apical (B1), right upper lobe posterior (B2), right upper lobe anterior (B3), bronchus intermedius, right middle lobe, right middle lobe lateral (B4), right middle lobe medial (B5), right lower lobe superior (B6), right lower lobe medial basal (B7), right lower lobe anterior basal (B8), right lower lobe lateral basal (B9), right lower lobe posterior basal (B10), left main stem bronchus, left upper lobe apical posterior (B1 + 2), left upper lobe anterior (B3), superior lingular (B4),

inferior lingular (B5), left lower lobe superior (B6), left lower lobe anteromedial basal (B7–8), left lower lobe lateral basal (B9), and left lower lobe posterior basal (B10) sequential bronchi. Using this technique, airway abnormalities such as the presence or absence of obstructive lesions (intrinsic or extrinsic), endoluminal masses, or mucosal abnormalities can be defined precisely relative to bronchovascular anatomy.

Virtual bronchoscopy for thoracic malignancies

Accumulating data indicate that VB is extremely useful for the detection of partial or complete bronchial obstructions secondary to endoluminal tumors or extrinsic compression in cancer patients. In an early study Fleiter et al [11] compared VB (performed with a double-detector CT unit) and FB in 20 patients who had thoracic malignancies. VB images were created successfully in 19 of these patients; a strong heart pulsation produced a motion artifact that prevented accurate reconstruction in one individual. Areas of high-grade stenoses were identified accurately using both techniques; however, VB did not detect discrete malignant infiltration and extraluminal compression in five patients.

In a subsequent study Liewald et al [12] evaluated 30 lung cancer patients who had VB and FB. 3D images were created in all patients, and 13 obstructive lesions were seen equally well by VB and FB. VB demonstrated tracheobronchial anatomy beyond high-grade stenoses in two patients; however, mucosal lesions were not visualized by VB. Rapp-Bernhardt et al [13] observed no significant differences in the location or extent of airway stenoses detected by VB compared with FB in 21 patients who had esophageal cancers infiltrating the respiratory tract. In a subsequent study these authors observed that conventional CT scans had a sensitivity of 92.9% and a specificity of 100%, whereas VB had a sensitivity of 93.8% and a specificity of 99.7% for detection of airway stenoses in lung cancer patients [14].

Hoppe et al [15] compared the efficacy of noninvasive multidetector CT, which included VB images, axial CT, coronal reformatted images, and sagittal reformatted images, with that of FB. In their examination of 200 bronchial sections obtained from 20 lung cancer patients (15 patients had bronchial carcinoma and five did not have central airway disease), these investigators observed that VB was a highly accurate method for assessing the severity of tracheobronchial stenoses; images from VB correlated extremely well with those obtained by FB ($r = 0.91$).

In a recent study the authors prospectively evaluated VB and FB in 32 consecutive patients who had suspected thoracic malignancies [16]. VB images were obtained successfully in all patients during one or two 17-second end-inspiration breath-holds (Fig. 2 shows data from representative patient). FB was within normal limits in seven of 20 patients (35%), and VB correlated with FB in these individuals. FB revealed a total of 22 abnormalities in 13 patients; VB detected 18 of these abnormalities, including 13 of 13 obstructing lesions (> 50% luminal occlusion) and five of six endobronchial lesions with less than 50% luminal obstruction. VB did not detect three mucosal lesions identified by FB. Overall, the sensitivity of VB was 82% for detection of any abnormality in the respiratory tract, 100% for obstructing lesions, 83% for endoluminal lesions, and 0% for mucosal lesions. The specificity of VB was 100%.

In a subsequent prospective observer study the authors evaluated SHR-CT, VB, and conventional CT scans directly for detection of tracheobronchial malignancies in 44 patients [17]. Image acquisition and simulation of tracheobronchial anatomy were suc-

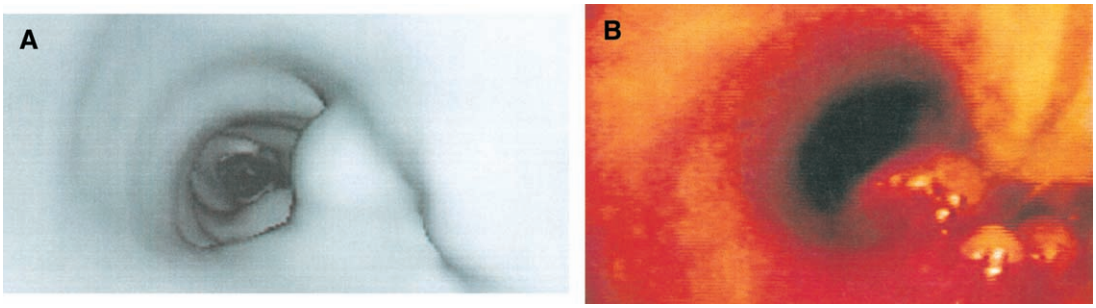

Fig. 2. Endoluminal lesion in 51-year-old man who had metastatic renal cell carcinoma metastatic to the right hilum. (*A*) VB. (*B*) FB. The lesion consists of large and small components in the right mainstem bronchus (*white arrows*) with complete obstruction of the right upper lobe bronchus. (Courtesy of US government.)

cessful in all individuals. Thirty-two patients had correlative FB within 1 month (Fig. 3 shows imaging from representative patient). SHR-CT and VB correlated with FB in nine patients who had normal anatomy; however, CT demonstrated two false-positive obstructing lesions in one patient. Twenty-three patients had a total of 35 abnormal FB findings. SHR-CT and VB detected 29 (83%) of these abnormalities accurately, including 19 of 19 obstructing lesions, 9 of 10 endoluminal masses, and one of six mucosal lesions.

SHR-CT and VB failed to detect a small peripheral endobronchial mass in one patient, mucosal inflammation in two patients, and the presence of blood without an identifiable source in three patients. It is possible that endobronchial bleeding was intermittent and not present at the time that SHR-CT and VB were obtained in these three individuals. In contrast, SHR-CT and VB demonstrated 10 and 11 additional lesions, respectively, that were not identifiable during FB because the size of the bronchoscope precluded evaluation of peripheral airways (in nine patients) or locations distal to high-grade stenoses (in two patients). Because many patients in this study underwent pulmonary resection, pathologic correlation was possible in nine patients; six obstructive lesions (67%) not detected by FB but visualized by SHR-CT and VB were confirmed to be malignant. Consistent with the authors' previous report [16], the sensitivities of SHR-CT and VB were 100% for obstructing lesions, 90% for endoluminal masses, and 17% for mucosal lesions. Specificities of SHR-CT and VB were 100%.

In contrast to the excellent imaging obtained with SHR-CT or VB, conventional CT scans were suboptimal for identification of airway pathology. Twenty-five patients who had bronchoscopic examinations and SHR-CT and VB also underwent conventional CT scanning. Seven patients (28%) had normal examinations by FB; results of conventional CT scans correlated with FB in six of these individuals (specificity 85%). Conventional CT scans depicted two false-positive lesions in one patient. Eighteen patients (72%) had a total of 29 abnormal FB findings. Conventional CT detected 17 of these abnormalities including 13 of 18 obstructive lesions, four of eight

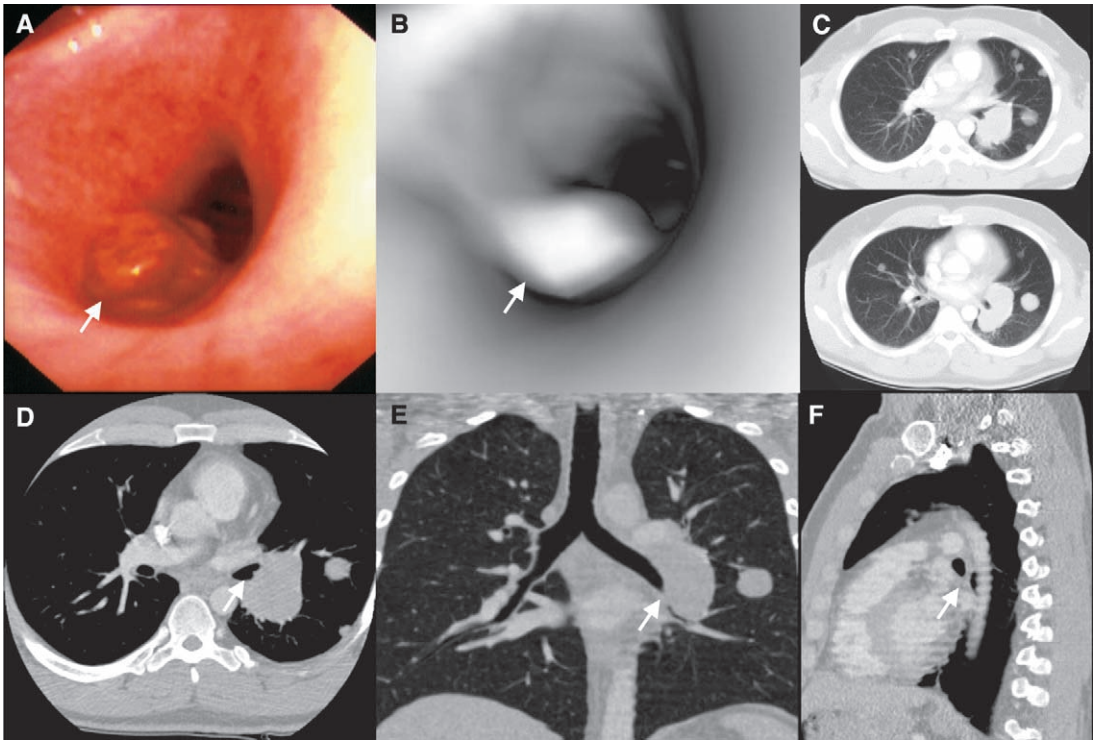

Fig. 3. Endoluminal lesion obstructing superior segment of left lower lobe in 30-year-old man who had metastatic melanoma FB (*A*), VB (*B*), and SHR-CT axial (*D*), coronal (*E*) and sagittal sections (*F*) all visualized this lesion (*white arrow*); however, this lesion was not appreciated on consecutive conventional CT sections (*C*). (Courtesy of US government.)

endoluminal masses, and zero of three mucosal lesions. As with SHR-CT and VB, obstructive lesions not visualized by FB were detected by conventional CT because of the size limitation of the bronchoscope. Three of six (50%) of these lesions were subsequently confirmed to be positive by histologic evaluation. In contrast to SHR-CT and VB, the sensitivity of conventional CT was 72% for obstructive lesions, 50% for endoluminal masses, 0% for mucosal lesions, and 59% overall. In no instance did conventional CT improve upon the findings of SHR-CT or VB.

Virtual bronchoscopy for benign disease

VB has been used to evaluate airway stenoses secondary to a variety of benign conditions [18–24]. Accumulating data indicate that VB has a sensitivity of 94% to 100% for detection of benign airway stenoses, and it is particularly useful for evaluation of high-grade stenoses and delineation of airway anatomy distal to these lesions, most of which are located in the central airways. Ferretti et al [25] demonstrated the utility of VB for evaluation of airway obstruction in patients who had Mounier-Kuhn disease, tracheomalacia, post-tracheostomy strictures, Wegener's granulomatosis, tracheopathia osteoplastica, and amyloidoses with tracheal wall involvement. These investigators also demonstrated the use of VB for the evaluation of airway compression by substernal goiters, aneurysms of the great vessels, and mediastinal tumors. Burke et al [23] evaluated VB in 21 patients who had primary tracheal strictures, eight patients who had tracheomalacia, two patients who had glottic webs, two patients who had tracheal granulomas, seven patients who had vocal cord immobility, and five patients who had innominate artery aneurysms. The length and width of fixed airway stenoses were demonstrated accurately by VB; stenosis-to-lumen ratios as determined by VB and FB varied less than 10%. VB was particularly helpful in evaluating high-grade airway stenoses that prevented full bronchoscopic assessment. VB was less useful for evaluation of dynamic airway obstructions, possibly because images were obtained during breath-hold at end-inspiration. Ferretti et al [25] obtained excellent VB images of dynamic airway compromise secondary to tracheomalacia by scanning at end-inspiration and end-expiration.

The authors' group conducted a prospective observer study recently comparing CT and VB to FB for evaluation of airway stenoses in patients who had Wegener's granulomatous [26]. Helical CT scans with 3D VB reconstruction of the trachea and bronchi were obtained in 11 patients. CT, VB, and FB were performed and evaluated in a blinded manner. Correlative FB was performed, on average, within 2 days of CT scans (Figs. 4, 5 show representative data from two patients). VB visualized 188 of 198 bronchi (95%). Conventional CT scans detected 22 stenoses, whereas VB revealed 31 of 40 stenoses identified by FB. Overall, this experience indicates that VB can demonstrate anatomy down to the segmental bronchi and that VB can detect the majority

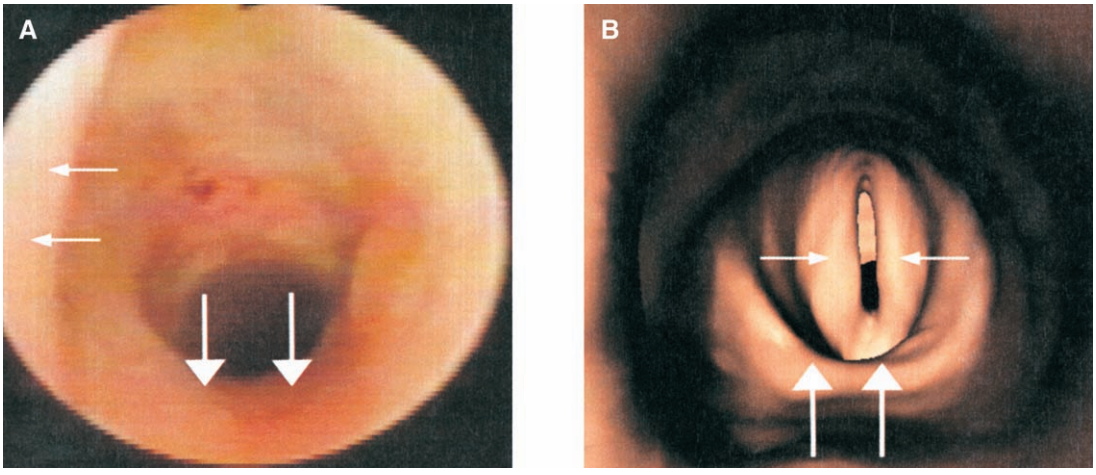

Fig. 4. Subglottic stenosis in patient who had Wegener's granulomatosis detected by way of (*A*) FB and (*B*) retrograde VB. The ability to reverse the viewing direction with the VB model is helpful in locating the stenosis. The stenosis appears to narrow the airway from the posterior aspect (*large arrow*). The vocal cords (*small arrows*) are shown to indicate the location of the stenosis in the subglottic region. (Courtesy of US government.)

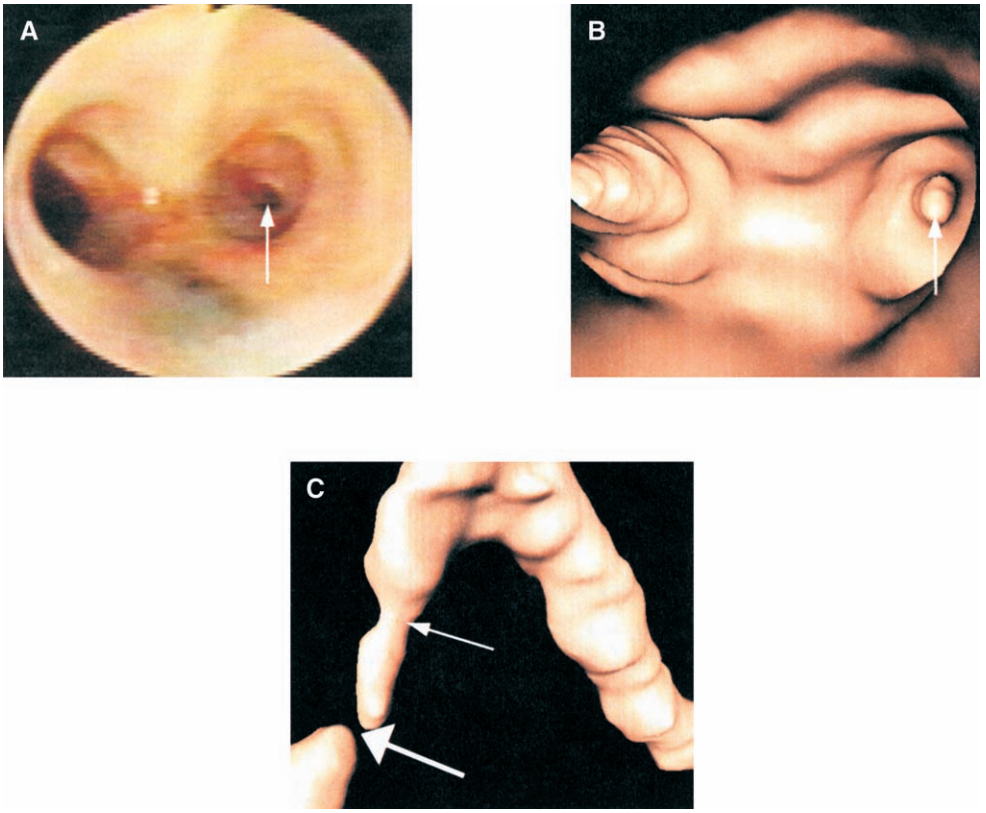

Fig. 5. Bronchus intermedius stenosis in patient who had Wegener's granulomatosis. (*A*) FB. (*B*) Endoscopic VB view. (*C*) Exoscopic VB view. The viewpoint is in the distal trachea looking toward the main carina. This series of pictures shows the left and right mainstem bronchus and the stenotic bronchus intermedius. The *large arrow* shows the extrastenotic region of the bronchus intermedius that is only visible on the exoscopic VB view. The *small arrows* show the other stenotic region of the bronchus intermedius that is visible on all views. (Courtesy of US government.)

of central airway stenoses in patients who have advanced Wegener's granulomatosis.

Summary

The data presented above indicate that VB is a novel and extremely useful modality for airway evaluation in patients who have benign and malignant disease. VB is noninvasive, with no additional radiation exposure relative to standard CT scans of the chest. Commercial software allows for the interactivity of 2D and 3D images. The ability to examine 2D and 3D anatomic detail from multiple directions enables precise assessment of intraluminal and extraluminal pathology. The authors' experience indicates that VB is a superb modality for assessing the length of airway stenoses and ascertaining airway patency distal to these lesions (Fig. 6). As such, VB has proven to be extremely useful for determining the feasibility of endobronchial procedures such as dilations, stent placements, and laser ablation of endobronchial tumors. Ferretti et al [27] observed that VB is an excellent noninvasive means for long-term monitoring of tracheobronchial stents. Furthermore, the authors have found VB useful for guiding the bronchoscopic evaluation of patients who have intermittent hemoptysis secondary to lesions in peripheral airways. The 3D anatomic detail provided by VB has proven useful for assessing the feasibility of lung-sparing procedures in patients who have limited pulmonary reserve and for sequentially evaluating treatment response in patients who have inoperable disease.

Currently, the main limitation of VB pertains to its inability to evaluate the mucosal surface of the respiratory tract reliably. Although form can be detected, mucosal color, irregularity, or friability cannot

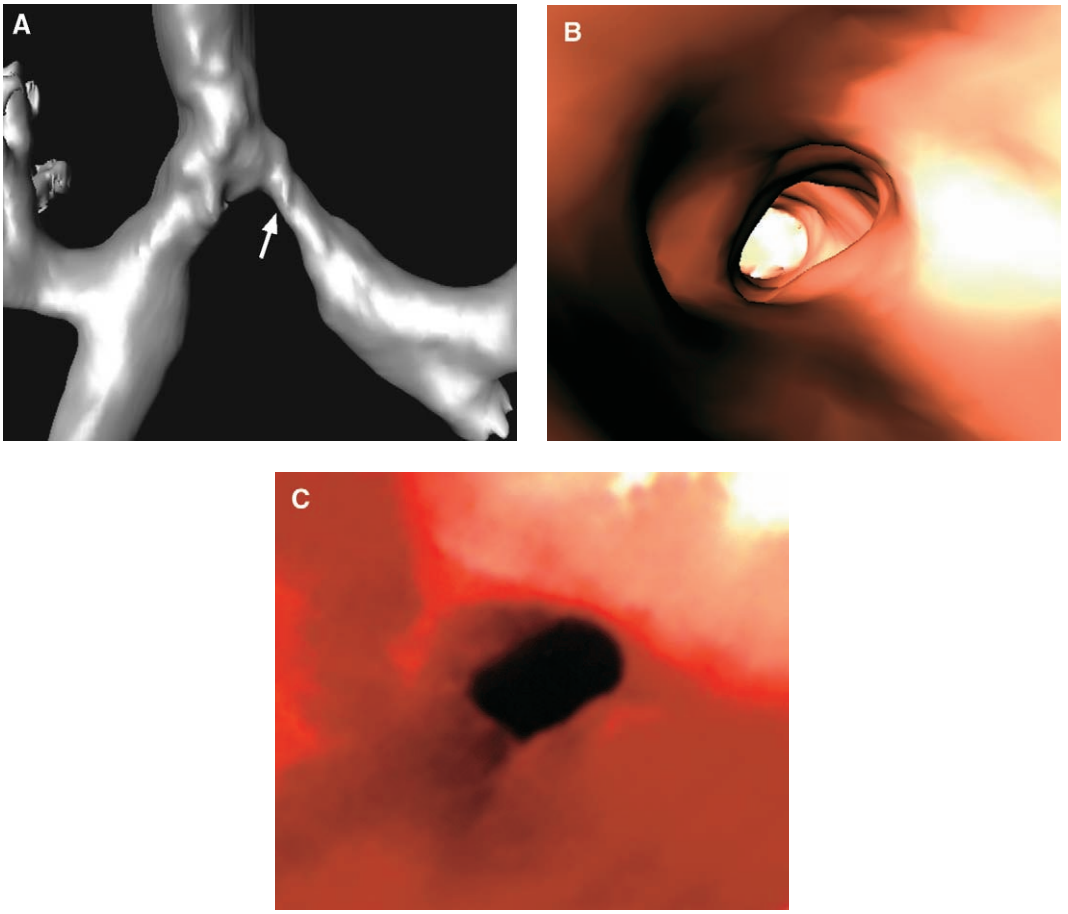

Fig. 6. (*A*, *B*) Virtual bronchoscopy revealing high-grade obstruction of the proximal left mainstem bronchus in lung cancer patient. (*C*) Fiberoptic bronchoscopy confirmed tumor recurrence.

be assessed. As such, VB cannot be used for routine surveillance of patients at high risk of developing airway malignancies. The development of novel aerosolized contrast agents or spectroscopic techniques that can discriminate benign versus malignant mucosal tissues might enhance the sensitivity and specificity of VB for the detection of preinvasive cancers within the respiratory tract.

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