Overview of Interventional Pulmonology for Radiologists

Daniel B. Green, MD
Lauren K. Groner, DO
Jared J. Lee, MD
James Shin, MD
Jordi Broncano, MD
Daniel Vargas, MD
Mario Castro, MD, MPH
Eugene Shostak, MD

Abbreviations: APC = argon plasma coagulation, BLVR = bronchoscopic lung volume reduction, BT = bronchial thermoplasty, CAO = central airway obstruction, EBB = endobronchial brachytherapy, EBUS = endobronchial US, ENB = electromagnetic navigational bronchoscopy, IPC = indwelling pleural catheter, TBNA = transbronchial needle aspiration, 3D = three-dimensional

RadioGraphics 2021; 41:1916–1935

https://doi.org/10.1148/rg.2021210046

Content Codes: CH CT IR

From the Departments of Radiology (D.B.G., L.K.G., J.S.) and Cardiothoracic Surgery (E.S.), Weill Cornell Medicine, 525 E 68th St, Box 141, New York, NY 10065; Departments of Medicine (J.J.L.) and Radiology (D.V.), University of Colorado, Aurora, Colo; Department of Radiology, Hospital San Juan de Dios, Córdoba, Spain (J.B.); and Division of Pulmonary and Critical Care Medicine, University of Kansas Medical Center, Kansas City, Kan (M.C.). Recipient of a Cum Laude award for an education exhibit at the 2020 RSNA Annual Meeting. Received March 5, 2021; revision requested April 5 and received May 17; accepted May 23. For this journal-based SA-CME activity, the author M.C. has provided disclosures (see end of article); all other authors, the editor, and the reviewers have disclosed no relevant relationships. **Address correspondence to** D.B.G. (e-mail: *dag2017@med.cornell.edu*).

SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- List the various types of interventional pulmonology procedures and their indications.
- Identify thoracic pathologic conditions that are amenable to treatment with interventional pulmonology procedures.
- Describe the imaging features of outcomes and complications of interventional pulmonology procedures.

See www.rsna.org/education/search/RG.

Interventional pulmonology is a growing field specializing in minimally invasive procedures of the mediastinum, lungs, airways, and pleura. These procedures have both diagnostic and therapeutic indications and are performed for benign and malignant diseases. Endobronchial US has been combined with transbronchial needle aspiration to extend tissue sampling beyond the airways and into the lungs and mediastinum. Recent innovations extending the peripheral access of bronchoscopy include electromagnetic navigational bronchoscopy and thinner bronchoscopes. An important indication for therapeutic bronchoscopy is the relief of central airway obstruction, which may be severe and life threatening. Techniques for restoring patency of the central airways include mechanical debulking and multiple modalities for ablation, stent placement, and balloon bronchoplasty. Bronchoscopic lung volume reduction improves quality of life in certain patients with severe emphysema and is an important less invasive alternative to lung volume reduction surgery. Bronchial thermoplasty is likewise a nonpharmacologic treatment in patients with severe uncontrolled asthma. Many of these procedures have unique selection criteria that require precise evaluations at preprocedure imaging. Postprocedure imaging is also essential in determining outcome success and the presence of complications. Radiologists should be familiar with these procedures as well as the relevant imaging features in both planning and later surveillance. Evolving techniques that may become more widely available in the near future include robotic-assisted bronchoscopy, bronchoscopic transparenchymal nodule access, transbronchial cryobiopsy, ablation of early-stage cancers, and endobronchial intratumoral chemotherapy.

An invited commentary by Wayne et al is available online.

Introduction

Interventional pulmonology is a quickly evolving subspecialty of pulmonary medicine offering minimally invasive procedures of the mediastinum, lungs, airways, and pleura. The range of procedures includes diagnostic and therapeutic options for both benign and malignant diseases. Imaging plays a key role in identifying patients who will benefit from interventional pulmonology procedures, detailing the relevant anatomy and measurements for procedure planning, and monitoring patients for successful outcomes and complications (Table 1). This article provides an overview of interventional pulmonology that is intended for practicing radiologists.

TEACHING POINTS

- During ENB, the patient lies on an electromagnetic mat that links to a sensor on a steerable navigation catheter, or locatable guide. The survey bronchoscopy is then registered to the virtual bronchoscopy, generating an airway road map to the specified target.
- The pneumothorax rate for ENB is 3%–6% with chest tube placement in 1.6%–2.9% of cases. Percutaneous CT-guided biopsy requires chest tube placement for pneumothorax in approximately 6.6% of cases but has a better diagnostic yield.
- Important features of CAO to identify are the degree and type of stenosis (intrinsic, extrinsic, or mixed), location and length, proximity to branch points, airway diameter proximal and distal to the stenosis, and patency of the airway distal to the stenosis, which is a predictor for better outcome.
- Approved by the U.S. Food and Drug Administration in 2018, BLVR treats emphysema with one-way endobronchial valves placed into a single lobe, preventing air entry while allowing air and mucus to exit. Target lobe collapse after valve placement results in improved exercise tolerance, oxygen requirements, and overall quality of life.
- Pre-BLVR evaluation involves a noncontrast volumetric chest CT at full inhalation, performed with a multidetector scanner with thin-section acquisition (0.6–1.25 mm), overlap, and a low-frequency reconstruction kernel. The measurements derived from quantitative CT analysis are the emphysema score, heterogeneity score, and fissure integrity.

Training and Certification

Physicians completing pulmonary and critical care fellowships have the option of advanced subspecialty training in interventional pulmonology. In 2007, there were only five dedicated interventional pulmonology fellowships in the United States, but by 2020, there were 38 accredited programs (1,2). The American Association for Bronchology and Interventional Pulmonology (AABIP) has offered an annual board certification examination since 2013 (3). As of 2017, completion of an accredited interventional pulmonology fellowship is a mandatory prerequisite for AABIP certification. However, practitioners without interventional pulmonology fellowship training or board certification are not limited from performing interventional pulmonology procedures, nor should this standard limit patient access to optimal care.

Types of Bronchoscope

Rigid Bronchoscope

The field of bronchoscopy began in 1897 when German laryngologist, Gustav Killian, successfully removed a foreign body from a patient's right main bronchus with a modified rigid esophagoscope and forceps (4). Previously, the laryngoscope only provided visualization of the trachea. After various alterations, the modern rigid bronchoscope is now a straight hollow stainless steel tube ranging from 5 to 14 mm in inner diameter, with multiple ports proximally for ventilation and multiple side holes distally for suctioning and cross ventilation (Fig 1). Because of the size and stiffness of the bronchoscope, rigid bronchoscopy requires general anesthesia and maintains airway patency in patients with respiratory failure.

Although it fell out of favor after development of the flexible bronchoscope, rigid bronchoscopy is now an essential tool in the interventional pulmonology arsenal. In addition to foreign body removal, it helps diagnose and treat both benign and malignant diseases of the trachea and main bronchi, usually in combination with other tools passed through its lumen. It also has a beveled distal end for tumor débridement and quick airway recanalization.

Flexible Bronchoscope

The first flexible bronchoscope was developed in the 1960s by a team led by Japanese thoracic surgeon Shigeto Ikeda (5). With improved maneuverability allowing access to subsegmental airways, bronchoscopists could visualize and sample material from the lower respiratory tract for diagnosis of infectious, inflammatory, and malignant diseases. Many new innovations followed, including bronchial brushing, bronchoalveolar lavage, and transbronchial needle aspiration (TBNA).

The main components of a flexible bronchoscope are the *(a)* suction port; *(b)* working channel port, through which various tools are passed; and *(c)* flexible insertion cord, which contains the working channel and an optical device for light and image transmission (Fig 1). The distal tip of most flexible bronchoscopes provides a 120° field of view and bends for wider visualization.

Nowadays, most flexible bronchoscopy examinations are performed for diagnostic purposes. The treatment of central airway obstruction (CAO) with a flexible bronchoscope alone is not recommended, although it can be passed through the lumen of a rigid bronchoscope to more distal lesions. Flexible bronchoscopy is generally safe, with a low rate of complications such as pneumothorax, bleeding, laryngospasm, bronchospasm, and transient hoarseness.

Diagnostic Bronchoscopy

Endobronchial US

Endobronchial US (EBUS) provides real-time visualization of structures adjacent to the airways during bronchoscopy. Introduced in 2003, convex-probe EBUS, or linear EBUS, incorporates a US transducer into the tip of a flexible bronchoscope and guides TBNA of mediastinal lymph nodes and other masses along the central airways.

Table 1: Imaging Findings before and after Bronchoscopy

Procedure	Important Preprocedure Imaging Findings	Intended Postprocedure Imaging Findings	Unintended Postprocedure Imaging Findings
ENB	Nodule size and location CT bronchus sign	No change expected	Pneumothorax Hemorrhage
Therapeutic bronchoscopy for CAO (mechanical debulking, ablation, stent placement, balloon bronchoplasty)	Location of the stenosis Proximity to the branch points Degree of the stenosis Type of stenosis (intrinsic, extrinsic, mixed) Length of the stenosis Airway diameter proximal and distal to the stenosis Patency of airway distal to the stenosis	Restoration of airway patency Metallic stent is visible at radiography Silicone stent is not visible at radiography	Pneumomediastinum Pneumothorax Stent migration Ingrowth of granulation tissue (silicone stents)
BLVR	Emphysema severity Heterogeneity Fissure integrity Zonal perfusion	Endobronchial valves Lobar collapse	Pneumothorax Valve migration Pneumonia
BT	Most poorly ventilated regions at hyperpolarized ^{129}Xe MRI	Not routinely obtained	Peribronchial consolidation Ground-glass opacities Septal thickening Bronchial occlusion Bronchial dilatation Atelectasis Pleural effusion
Talc pleurodesis	Recurrent pleural effusion	Decreased pleural fluid High-attenuation talc accumulations Increased uptake at PET	Ipsilateral pneumonitis Re-expansion pulmonary edema
IPC placement	Recurrent pleural effusion	Decreased pleural fluid Catheter in place	Pneumothorax due to air leak Loculated pneumothorax due to nonexpanding lung (CT images may also show visceral pleural thickening) Re-expansion pulmonary edema Empyema Catheter tract metastases Cellulitis

Note.—BLVR = bronchoscopic lung volume reduction, BT = bronchial thermoplasty, CAO = central airway obstruction, ENB = electromagnetic navigational bronchoscopy, IPC = indwelling pleural catheter, ^{129}Xe = xenon-129.

Convex-probe EBUS provides a 90° view parallel to the transducer, is equipped with Doppler US, and guides real-time tissue sampling (Fig 2). EBUS-guided TBNA is more accurate than CT or PET in staging the mediastinum in patients with lung cancer, with a pooled sensitivity of 89% and specificity approaching 100% (6,7).

Radial-probe EBUS integrates a US transducer into a free-standing probe that can be advanced through the working channel of a flexible bronchoscope. Radial-probe EBUS provides anatomic detail of the tracheal wall with better sensitivity than CT in distinguishing tumor invasion from extrinsic compression (8). However, its most common use is in evaluating pulmonary lesions, particularly those in the periphery. The US image displays the transducer centrally with a 360° view around the airway (Fig 2). Normal lung is echogenic because of the strong reflector properties of air. Noncalcified lung lesions are typically hypoechoic and project alongside or concentrically around the transducer dependent on their location relative to the bronchus. The major disadvantage of radial-probe EBUS is that the probe must be removed before tissue sampling.

Peripheral Bronchoscopy

Modifications for improving endobronchial access to peripheral lung lesions include radial-probe

RadioGraphics

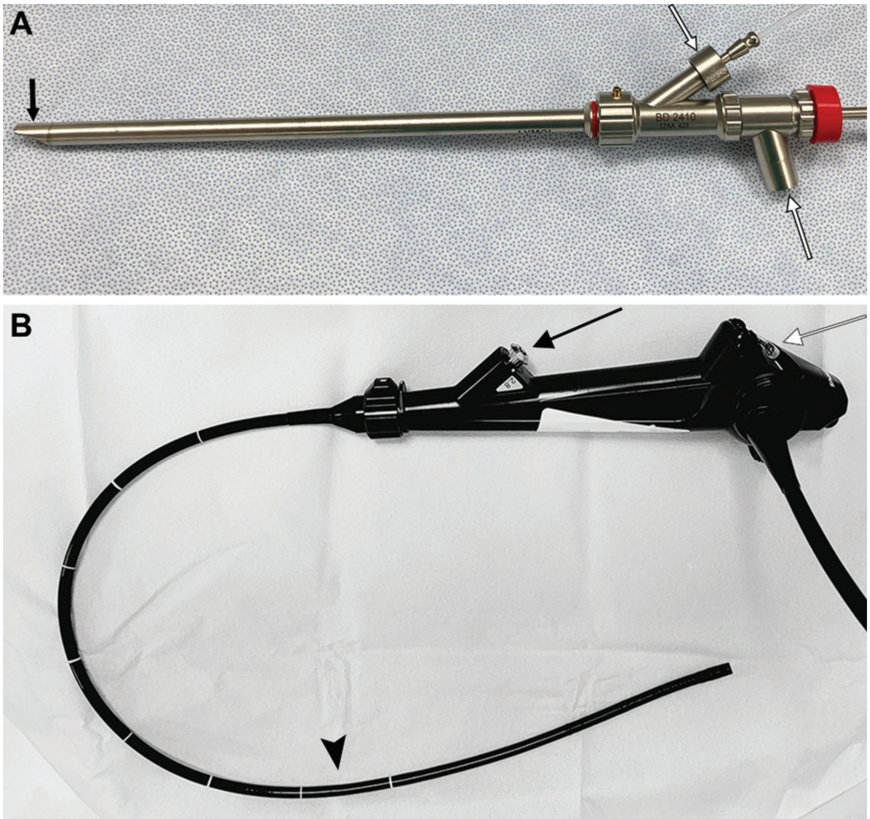


Figure 1. **(A)** The rigid bronchoscope is a straight hollow tube with side ports proximally (white arrows) and a beveled distal end (black arrow). **(B)** The flexible bronchoscope has a suction port (white arrow), working channel (black arrow), and a flexible insertion cord (arrowhead).

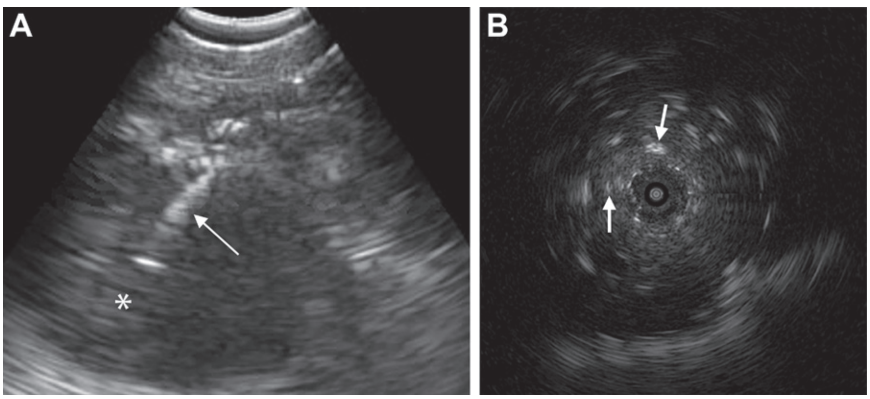


Figure 2. Two types of EBUS. **(A)** Convex-probe EBUS image shows a biopsy needle (arrow) within a mediastinal lymph node (*) 90° to the transducer. **(B)** Radial-probe EBUS image shows a pulmonary consolidation in a 360° view around the transducer. A few droplets of echogenic gas (arrows) are interspersed within the hypoechoic consolidation.

EBUS, ultrathin bronchoscopy, and electromagnetic navigational bronchoscopy (ENB). An ultrathin bronchoscope is a flexible bronchoscope with a 3-mm outer diameter that is capable of reaching one generation of bronchi farther than a standard thin bronchoscope. A recent single-center study achieved a diagnostic yield of 70.1% by using an ultrathin bronchoscope, compared with 58.7% with a thin bronchoscope (9).

ENB extends peripheral reach with guidance from preprocedure thin-section CT, which is segmented into virtual bronchoscopic images with proprietary software. Table 2 shows the required CT acquisition parameters, and a key feature is the degree of section overlap. During ENB, the patient lies on an electromagnetic mat that links to a sensor on a steerable navigation catheter or locatable guide. The survey bronchoscopy is then

Table 2: Chest CT Requirements for ENB Guidance

Attribute	Requirement
CT scanner	At least 16 detectors
Patient position	Supine
Breath hold	Full inhalation
Contrast agent	None
Matrix	512 × 512
Section thickness	≤1.25 mm
Section overlap*	20%–50%
Kernel filter	Standard soft tissue

*Overlap percentage = 100 × (section thickness – interval)/section thickness.

registered to the virtual bronchoscopy, generating an airway road map to the specified target. The locatable guide and an extended working channel are passed through the flexible bronchoscope, providing real-time feedback throughout the procedure. Fluoroscopy assists most cases and allows the bronchoscopist to make subtle adjustments (10). Radial-probe EBUS may be used to help confirm proximity to the target lesion but must be removed before TBNA.

The overall diagnostic yield of ENB is 65%–73% (10–12). The sensitivity for detecting cancer is 69%–71%, but the negative predictive value is only 52%–56% (10,11). The presence of the CT bronchus sign—an airway directly leading to a lesion and becoming occluded or continuing through the lesion as an air bronchogram—helps improve diagnostic success rates. In a prospective study of 51 patients, ENB was diagnostic in 79% of cases with a CT bronchus sign but in only 31% otherwise (13). Greater nodule size and visualization with radial-probe EBUS are also associated with increased diagnostic yield (9,12).

Conventional ENB lacks real-time guidance to account for lesion divergence due to changing lung volume. Digital fluoroscopic tomosynthesis and cone-beam CT have shown promise in depicting lesions that are not visible with conventional fluoroscopy. The acquired real-time dataset, referred to as augmented fluoroscopy, modifies the virtual target on the basis of updated registration with the planning CT (Fig 3). A recent retrospective study showed a diagnostic yield of 79% for ENB with digital tomosynthesis compared with 54% with ENB alone (14). Studies of cone-beam CT showed a diagnostic yield of 70%–84% when assisting ENB (15–17). Additional comparative studies are needed to corroborate these data and further evaluate radiation exposure.

Potential radiographic findings after ENB include pneumothorax and transient increased opacity surrounding the target lesion due to hemorrhage or retained lavage fluid (if performed). The pneumothorax rate for ENB is 3%–6% with chest tube placement in 1.6%–2.9% of cases (10–12). Percutaneous CT-guided biopsy requires chest tube placement for pneumothorax in approximately 6.6% of cases but has a better diagnostic yield (18). The postbiopsy bleeding rate is similar for the two techniques at about 1% of patients (12,18).

Therapeutic Bronchoscopy

CAO is defined as greater than 50% cross-sectional narrowing of the trachea, main bronchi, bronchus intermedius, or lobar bronchi. Clinical signs include dyspnea, hemoptysis, wheezing, postobstructive pneumonia, and respiratory failure. Malignant CAO is separated into intrinsic masses (primary tumors and endoluminal metastases), extrinsic compression (lymphadenopathy or tumors such as primary lung, esophageal, and thyroid cancer), and mixed lesions (generally originating in the mediastinum and invading the airway). Causes of benign CAO include benign tumors, granulomatosis with polyangiitis, radiation therapy, lung transplant, tuberculosis and other infections, sarcoidosis, and prior intubation.

Treatment of malignant CAO is typically palliative because of its advanced stage, and surgery is usually not indicated. While chemotherapy and radiation therapy can take weeks to relieve an obstruction, therapeutic bronchoscopy provides immediate relief in 93% of patients, although only about 48% experience clinical improvement (19). Endobronchial therapies for malignant CAO are summarized in Table 3. An overall adverse event rate of 2.2% varies across institutions, and complications are more frequent than in benign CAO (20,21). A delay in treatment decreases the likelihood of a successful outcome, highlighting the importance of recognizing CAO at CT.

Important features of CAO to identify are the degree and type of stenosis (intrinsic, extrinsic, or mixed), location and length, proximity to

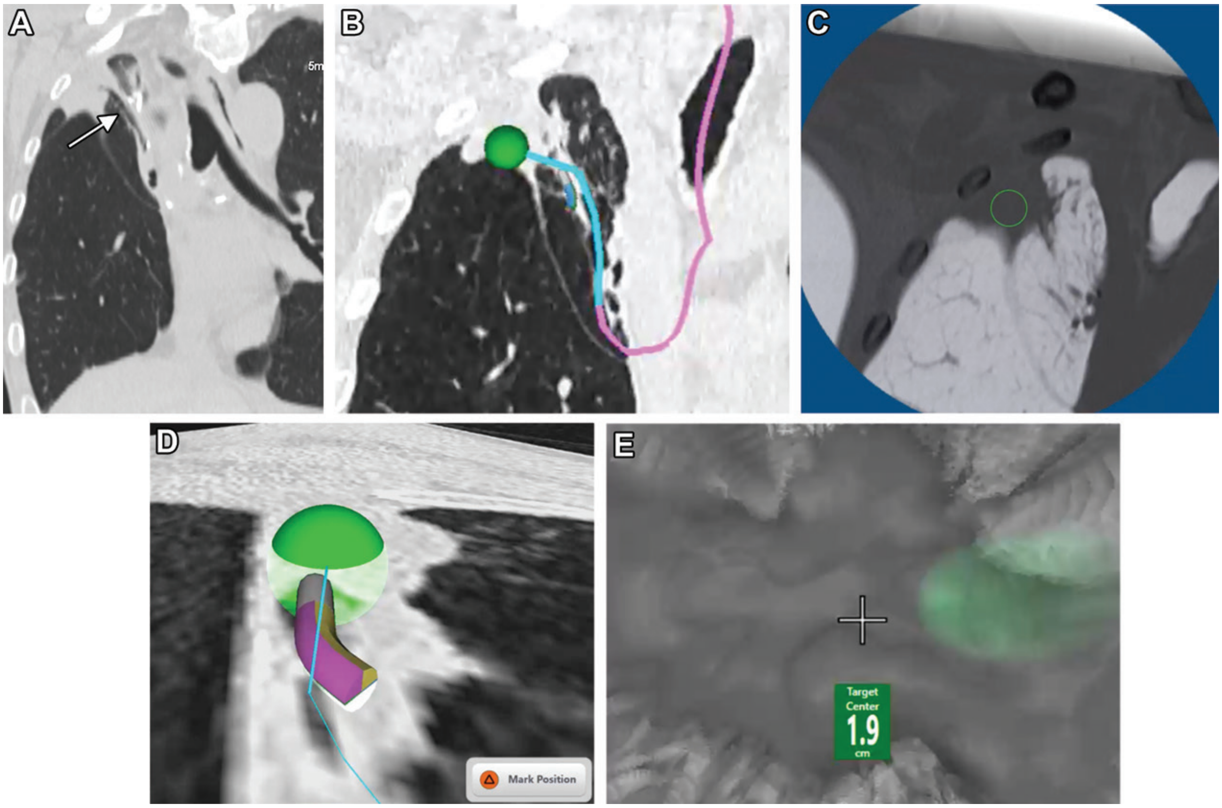


Figure 3. New right apical pulmonary lesion after right upper lobectomy in a 66-year-old man with lung cancer. **(A)** Coronal CT image shows the lesion peripherally with an approaching bronchus (arrow). **(B)** Coronal CT image that was uploaded for guidance shows the path of the flexible bronchoscope (purple line), the path of the extended working channel (blue line), and the target lesion (green ball). **(C)** Fluoroscopic tomosynthesis image from a fluoroscopy sweep shows the lesion (circle), which was not seen at conventional fluoroscopy. **(D)** CT-guided road map shows the locatable guide (purple catheter) approaching the virtual target (green ball). **(E)** Corresponding real-time image generated from fluoroscopic tomosynthesis confirms the location of the actual target (+).

branch points, airway diameter proximal and distal to the stenosis, and patency of the airway distal to the stenosis, which is a predictor for better outcome (22). Assessment of airway invasion with extrinsic lesions is not reliable at CT when limited to the wall. Projection into the lumen, mucosal thickening, and interruption of calcified cartilage are more definitive signs of invasion.

For CAO due to tracheobronchomalacia, dynamic expiratory CT should be performed because it induces a greater degree of luminal narrowing than end-expiratory imaging and is more sensitive for diagnosis (23). Some institutions use a 70% reduction of anterior-posterior diameter rather than 50% to improve specificity. For other causes of CAO, there is no standardized measurement method for cross-sectional luminal narrowing. Although CT acquisition at full inhalation is ideal, breath holding in many patients with CAO is limited. An estimate of the degree of luminal narrowing is usually sufficient, as the decision to intervene is not based on a single measurement but on several factors such as suspected cause (benign or malignant), type of stenosis, lesion extent, patient condition, bronchoscopic appearance, and anticipated response to therapy. The main imaging finding after successful treatment of CAO is improved airway patency. Rarely, perforation results in pneumomediastinum, pneumothorax, hematoma, or fluid collection.

Mechanical Debulking

Mechanical debulking is the physical removal of tissue from the central airways for both diagnostic and therapeutic purposes. The most common complication is bleeding, although it is usually minor and easily controlled (24). Forceps and the beveled tip of a rigid bronchoscope are the main débridement tools. Rigid bronchoscopic debulking is ideal for larger pieces of tissue, while forceps are favored for more precise tissue removal. A microdébrider is a motorized debulking tool that is capable of fine débridement and simultaneous suction.

Ablative Procedures

Ablation directly destroys tissue and can be divided into modalities utilizing heat (laser, electrocautery, and argon plasma coagulation [APC]) or cold (cryotherapy) and those with

Table 3: Endobronchial Treatment Modalities in Malignant CAO

Treatment Modality	Endoluminal Tumor	Extrinsic Compression	Immediate Effect	Risk of Airway Fire	Major Indications
Mechanical debulking	+	−	+	−	Immediate restoration of patency; tissue sampling
Electrocautery	+	−	+	+	Hemostasis after tumor debulking
Laser therapy	+	−	+	+	Immediate restoration of patency
APC	+	−	+	+	Hemostasis after tumor debulking
Cryotherapy	+	−	−	−	Preserves tissue architecture for biopsy
Cryoadhesion	+	−	+	−	Immediate restoration of patency
Photodynamic therapy	+	−	−	−	Palliative restoration of obstructed airway; definitive therapy for carcinoma in situ
Brachytherapy	+	−	−	−	Alternative or adjunct to external radiation therapy
Stent placement	+	+	+	−	Resists extrinsic compression after other debulking techniques
Balloon bronchoplasty	+	+	+	−	Complement to other debulking techniques
Intratumoral chemotherapy	+	+	−	−	Potential off-label alternative to stent placement as a complement to other debulking techniques

Note.—APC = argon plasma coagulation. + indicates yes, − indicates no.

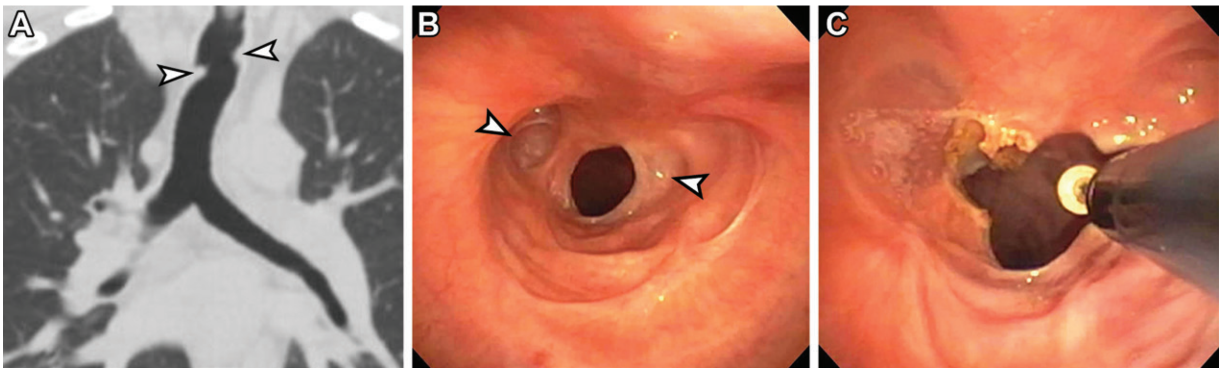


Figure 4. Postintubation tracheal stenosis in a 31-year-old man. **(A)** Coronal CT image shows tracheal narrowing due to a web (arrowheads). **(B, C)** Bronchoscopic images show the stenosis (arrowheads in **B**) before (**B**) and during (**C**) electrocautery.

immediate (laser, electrocautery, and APC) or delayed (cryotherapy, photodynamic therapy, and brachytherapy) effect. The ideal lesion for ablation is intraluminal and focal. Ablation is contraindicated in extrinsic compression to avoid damaging normal mucosa and extensive lesions that cannot be fully visualized to ensure a salvageable distal airway. Prolonged sedation and reduced fraction of inspired oxygen (FiO_2)(to avoid airway fire during thermal ablation) are the main reasons for severe albeit rare complications such as respiratory failure, arrhythmia, and death (20).

Electrocautery.—Electrocautery uses an electric current to directly heat and destroy tissue. It is relatively cheap, widely available, and easy to use (25). It débrides tissue on its own or coagulates bleeding tissue after mechanical débridement or other ablative modalities. Although most frequently used for tumors, electrocautery can also disrupt benign stenotic webs (Fig 4). The rate of major complications is less than 1% (25).

Laser Therapy.—Laser therapy uses thermal energy that is produced as light and transferred to tissue (Fig 5). Although many types of biomedical laser technologies are available, the most commonly used is the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser. In addition to its immediate effect, thermal injury has a delayed effect for several days after application, further improving luminal patency. Laser therapy offers deeper tissue penetration than other ablative techniques, although high cost,

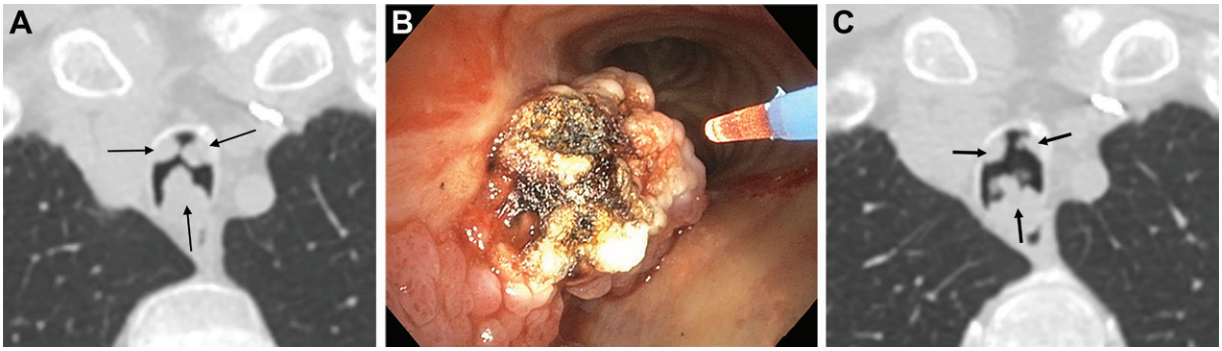


Figure 5. Laser therapy in a 73-year-old man with recurrent respiratory papillomatosis. **(A)** Axial CT image shows endotracheal papillomas resulting in severe obstruction (arrows). **(B)** Bronchoscopic image shows devitalized tissue after laser therapy. **(C)** Axial CT image obtained subsequently shows decreased size of the papillomas (arrows).

bulky size of the apparatus, and the need for protective eyewear limit its use.

Argon Plasma Coagulation.—APC is a noncontact electrocoagulation technique that heats adjacent tissue through a high-frequency current meeting argon gas at the probe tip. Because of its limited depth of effect, APC is usually a complementary technique for achieving hemostasis after débridement. Although it is generally considered safe and effective, gas embolism is an extremely rare but life-threatening complication (26). APC application in the trachea is associated with gas embolization to the right atrium through systemic veins, whereas APC in the bronchi results in gas embolization to the left atrium through pulmonary veins (27).

Cryotherapy.—Cryotherapy destroys tissue by controlled application of extreme cold energy directly onto target tissue, followed by multiple freeze-thaw cycles with temperatures as low as –90°C. Unlike thermal ablation techniques, the use of cryotherapy preserves tissue architecture for biopsy, does not require decreased FiO_2, and can remove foreign bodies with high water content. Because tissue necrosis takes days to weeks, cryotherapy is not suitable in patients who require immediate relief. Cryoadhesion is an alternative technique with instantaneous effect. The cryoprobe adheres to tissue and is then abruptly withdrawn along with an attached piece of tissue. Bleeding is the main complication (up to 12% of cases), but it is typically minor and easily coagulated (28).

Photodynamic Therapy.—Photodynamic therapy is approved for definitive treatment of central early-stage lung cancer and malignant CAO palliation. A photosensitizing drug is injected before photodynamic therapy and preferentially delivered to malignant cells with high metabolic activity. An endobronchial photodynamic therapy probe then emits a specific frequency at the target lesion, activating the photosensitizer and initiating necrosis. After several days, repeat bronchoscopy débrides nonviable tumor.

Endobronchial Brachytherapy.—Endobronchial brachytherapy (EBB) delivers palliative radiation in patients with symptomatic endoluminal or compressive tumors. A narrow-bore brachytherapy catheter is placed bronchoscopically and securely taped at the nostril. The catheter is then removed after EBB, and tissue necrosis ensues over the next several weeks.

EBB offers higher doses of localized radiation than external beam radiation therapy (EBRT), improving local control while sparing normal tissue. EBB can also be used in combination with EBRT, stent placement, or other ablative therapies. One randomized trial showed improved re-expansion of collapsed lung with EBB and EBRT compared with EBRT alone (29). However, a meta-analysis showed no conclusive evidence of symptom improvement or survival advantage with the addition of EBB and instead recommended EBB for symptomatic patients who are not candidates for further chemotherapy or EBRT (30). The main complication is fatal hemoptysis, with rates ranging from 7% to 22% in randomized trials (31).

Patient selection, optimal catheter positioning, and treatment planning are determined with CT features of CAO. For patients undergoing chest radiography before radiation therapy, the brachytherapy catheter has a small radiopaque marker at the tip and should not be mistaken for a misplaced enteric tube (Fig 6). A successful response to EBB results in improved airway patency and reaeration of previously collapsed lobes.

Stent Placement

Airway stents are endoluminal prostheses designed to maintain or restore airway patency in symptomatic patients. Stents treat both benign and malignant disease, and most experts agree they should

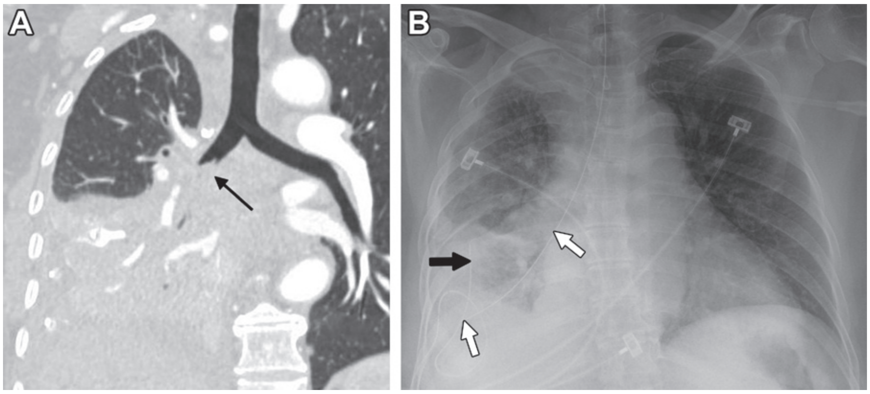
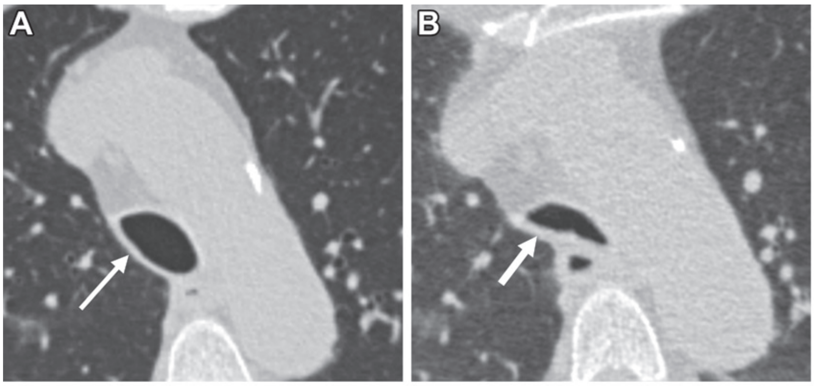


Figure 6. Palliative EBB in a 66-year-old woman with metastatic non–small cell lung cancer. **(A)** Coronal CT image shows persistent occlusion of the bronchus intermedius (arrow), with right middle and lower lobe collapse. The patient then underwent flexible bronchoscopy with balloon dilation of the bronchus intermedius and EBB catheter placement into the right middle lobe. **(B)** Frontal chest radiograph obtained after placement shows improved aeration of the right lung base and the brachytherapy catheter with a small radiopaque marker at the tip (white arrows). Note the indwelling pleural catheter (black arrow).



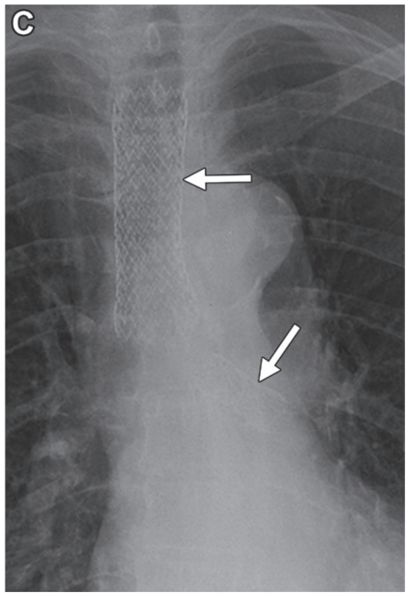


Figure 7. Metallic stents in an 81-year-old woman with progressive cough and multiple prior pneumonia diagnoses. **(A)** Axial CT image in inhalation shows a lunate appearance of the trachea, suggesting tracheomalacia (arrow). **(B)** Axial CT image in dynamic exhalation shows further anterior-posterior narrowing of the trachea (arrow). Left main bronchus narrowing is not shown. Dynamic bronchoscopy with forced expiratory maneuvers confirmed the diagnosis of tracheobronchomalacia, and metallic stents were placed as a short-term trial. **(C)** Frontal chest radiograph obtained subsequently shows metallic stents (arrows) in the trachea and left main bronchus.

be reserved for palliative measures when other techniques are unsuccessful or infeasible (32). Indications include extrinsic compression, benign strictures, tracheomalacia, and healing of a fistula or anastomotic dehiscence. The overall complication rate is 3.9% (20).

Silicone and metallic stents are the main types in current use. Silicone stents, which require rigid bronchoscopy for placement, are the most widely used and favored for benign stenoses. They are customizable, adjustable after deployment, and can be easily removed. The main complication is stent migration in 9.5% of cases (33). Granulation tissue ingrowth at the proximal or distal end and obstruction due to secretions are less frequent complications. Bifurcating silicone stents (Y-stents) are useful for carinal or bilateral main bronchial involvement.

Metallic stents can be deployed during flexible bronchoscopy, but many bronchoscopists prefer rigid bronchoscopy. The incidence of migration is lower than that of silicone stents, but they are more difficult to adjust and remove (34). Metallic stents are mainly used for malignant CAO but can be used for short-term trials in benign disease or when rigid bronchoscopy is not feasible for silicone stent placement.

In addition to the aforementioned imaging features of CAO, the lengths of landing zones proximal and distal to the stenosis are necessary for stent selection and planning. Metallic stents are MRI conditional. At radiography and CT, they have high attenuation with a latticelike structure (Figs 7, 8). Silicone stents cannot be visualized at chest radiography and are less highly attenuating at CT, with a uniform uninterrupted structure (Fig 9).

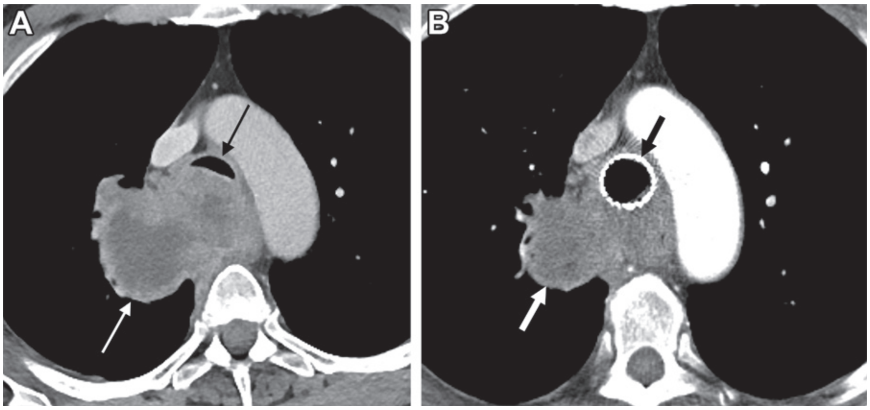


Figure 8. Metallic stents in a 70-year-old man with penile squamous cell carcinoma with worsening dyspnea. **(A)** Axial contrast-enhanced CT image shows a large mediastinal mass (white arrow) severely narrowing the trachea (black arrow). **(B)** Axial CT image obtained after metallic stent placement shows decreased size of the mass (white arrow) due to chemotherapy and a patent trachea with a stent (black arrow).

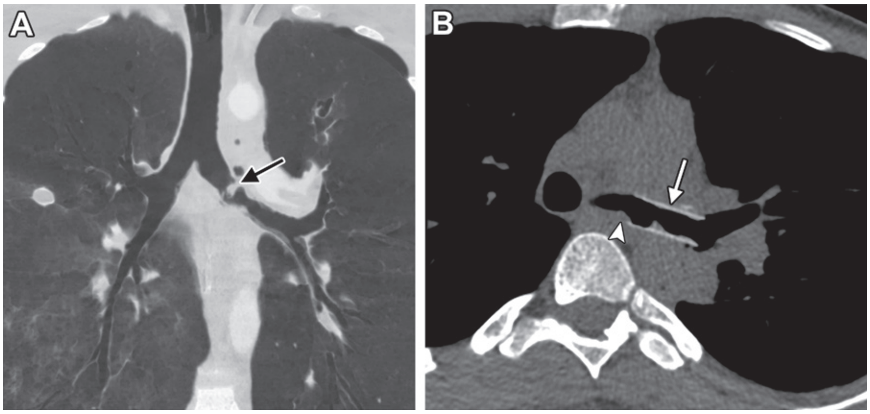


Figure 9. Silicone stent in a 22-year-old man who presented after a motor vehicle collision. **(A)** Coronal minimum intensity projection CT image shows a left main bronchus fracture (arrow). **(B)** Axial CT image obtained 2 months later shows a silicone stent (arrow) with soft tissue mildly narrowing the proximal end (arrowhead). The soft tissue was identified at subsequent bronchoscopy as granulation tissue and mechanically débrided with flexible forceps.

Developing stent technology includes biodegradable, drug-eluting, and customizable three-dimensional (3D)–printed silicone stents, which are patient- and lesion-specific designs derived from a CT dataset. Automated airway segmentation generates a 3D model with digital augmentation of the stenosis, and a 3D-printed stent model is then derived from the corrected airway anatomy (Fig 10).

Balloon Bronchoplasty

Balloon bronchoplasty dilates focal airway stenoses, which are most commonly from a benign cause (35) (Fig 11). While short-term results are generally good with immediate relief of symptoms, some patients require more than one dilation or additional treatment with laser or stent placement (36,37). The likelihood of long-term success depends on factors such as the cause, length, and severity of the stenosis at presentation.

Balloon bronchoplasty may be combined with other endobronchial treatments but is not suggested as a sole treatment of malignant CAO because of the high likelihood of restenosis (38). Balloon size is based on the diameter of the normal lumen proximal to the stenosis. For main bronchus stenosis near the carina, the contralateral main bronchus diameter is more indicative of balloon size. Balloon bronchoplasty is an overall safe procedure without significant complications (39). Microperforations may result in pneumomediastinum at postprocedure imaging but are usually not clinically significant.

Bronchoscopic Lung Volume Reduction

Approved by the U.S. Food and Drug Administration in 2018, bronchoscopic lung volume reduction (BLVR) treats emphysema with one-way endobronchial valves placed into a single lobe, preventing air entry while allowing air and mucus

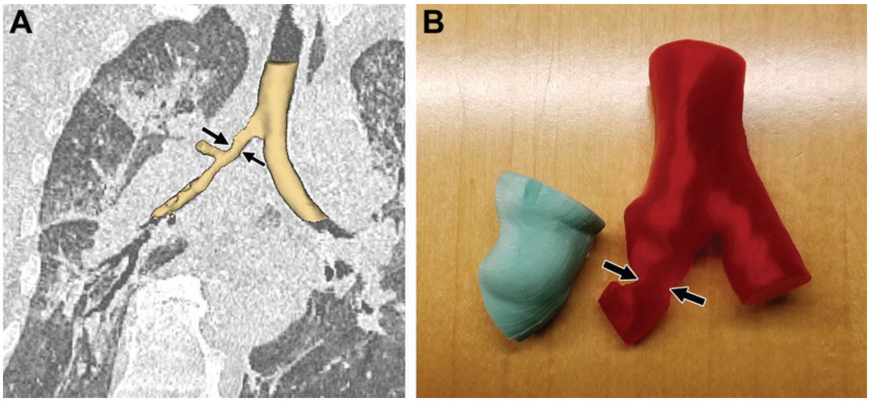


Figure 10. Custom 3D-printed silicone stent used to treat idiopathic right main bronchus stenosis in a 64-year-old man who presented with progressive shortness of breath. **(A)** Coronal oblique CT image with a segmented airway overlap in yellow shows the right main bronchus stenosis extending into the bronchus intermedius (arrows). **(B)** Photograph shows the digitally augmented stenotic airway model (red structure with arrows pointing to the stenosis), which forms the basis for a patient-specific silicone stent (green structure) incorporating dimensional specifications prescribed by the proceduralist. The stent was fabricated with liquid injection molding by using a custom 3D-printed mold.

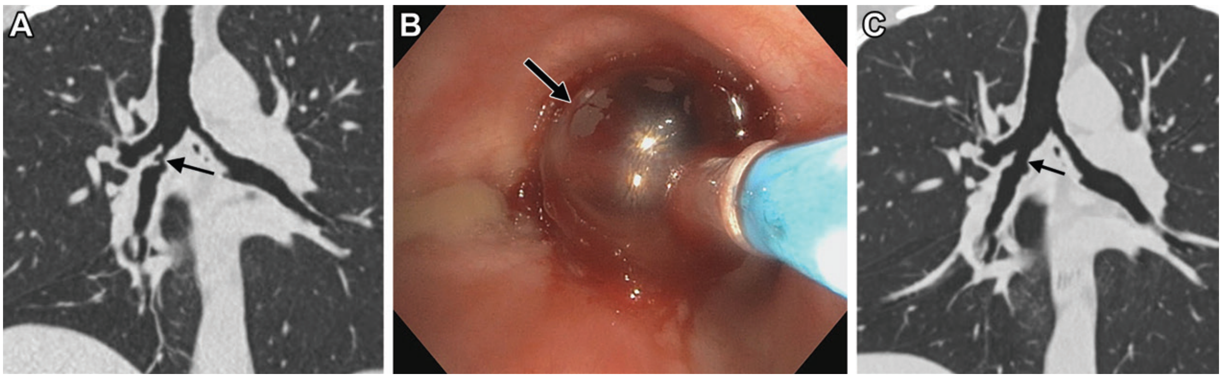


Figure 11. Balloon bronchoplasty in a 48-year-old man with granulomatosis with polyangiitis who presented with increasing dyspnea and cough. **(A)** Coronal CT image shows severe stenosis of the bronchus intermedius (arrow). **(B)** Bronchoscopic image shows an inflated balloon (arrow) during bronchoplasty. **(C)** Coronal CT image obtained subsequently shows improved patency (arrow).

to exit. Target lobe collapse after valve placement results in improved exercise tolerance, oxygen requirements, and overall quality of life (40–44).

The National Emphysema Treatment Trial (NETT) demonstrated improved survival and quality of life after lung volume reduction surgery (LVRS) compared with standard medical treatment in participants with predominantly upper lobe emphysema and low baseline exercise capacity (45). However, many patients are not eligible for LVRS because of surgical risk. BLVR is a less invasive alternative that mimics the physiologic changes of LVRS, although outcome data comparing the two are lacking.

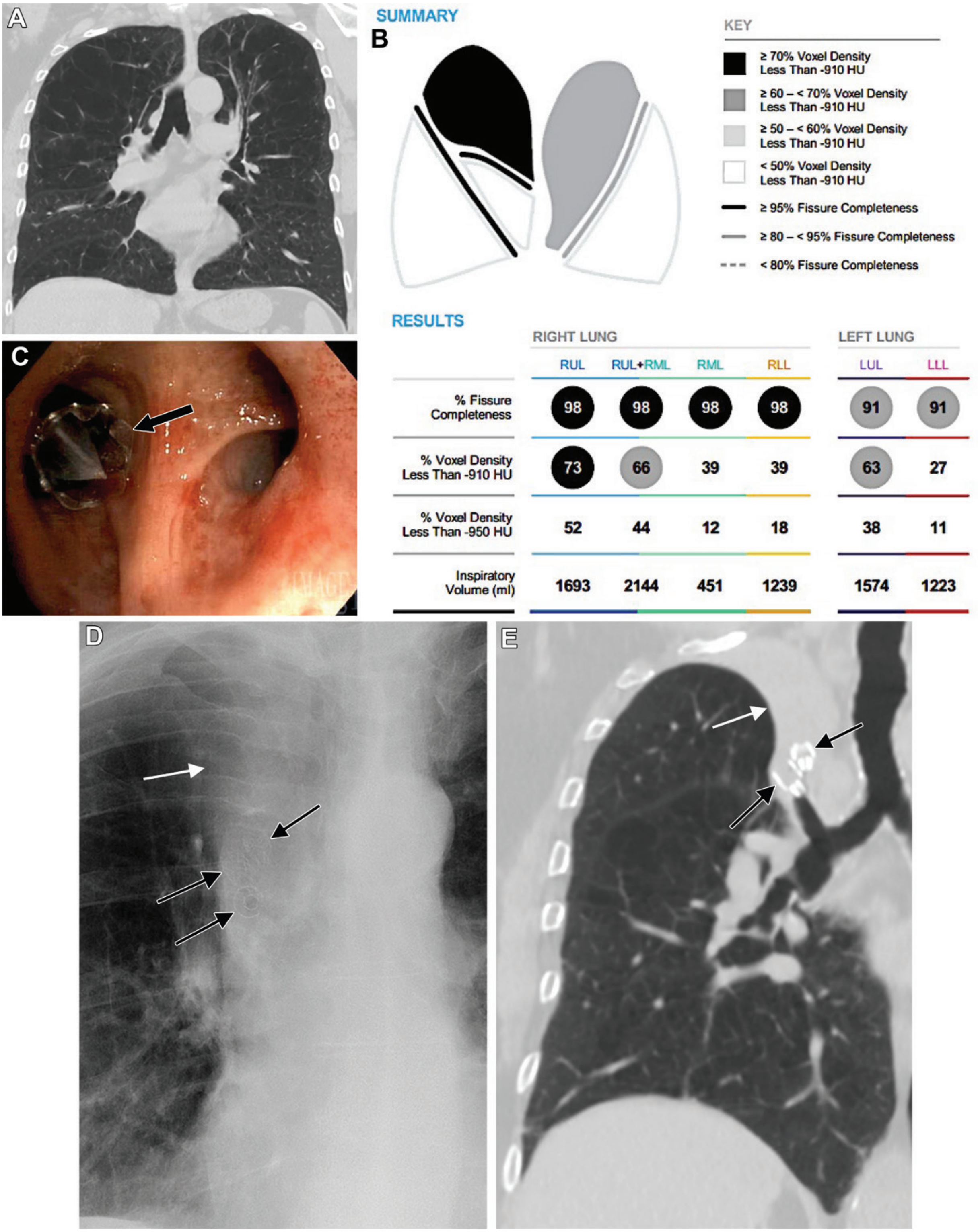
An endobronchial valve consists of a silicone valve within a nickel-titanium stentlike retainer covered by a silicone membrane. Currently, the two commercially available endobronchial valves supported by randomized control trial data are the Zephyr Valve (Pulmonx) and the Spiration Valve System (Olympus).

Ideal candidates for BLVR have severe chronic obstructive pulmonary disease (COPD) with reduced forced expiratory volume at 1 second (FEV_1) (15%–45% predicted), hyperinflated lungs (total lung capacity >100% predicted), and air trapping (residual volume >150% predicted), despite optimal medical therapy (40). Patients who are not suitable candidates have large bullae greater than one-third of either hemithorax, clinically significant bronchiectasis, incomplete fissures, nickel or silicone allergy, or other prohibitive medical conditions (43).

Pre-BLVR evaluation involves a noncontrast volumetric chest CT at full inhalation, performed with a multidetector scanner with thin-section acquisition (0.6–1.25 mm), overlap, and a low-frequency reconstruction kernel. The measurements derived from quantitative CT analysis are the emphysema score, heterogeneity score, and fissure integrity (Fig 12). While the most emphysematous lobes, degree of hetero-

RadioGraphics

Figure 12. Severe emphysema in a 66-year-old woman who presented for BLVR evaluation. **(A)** Coronal CT image shows heterogeneous emphysema that is most advanced in the upper lobes. **(B)** Quantitative CT analysis helps confirm the target is the right upper lobe, with a 73% emphysema score at –910 HU and 98% fissure completeness. *LLL* = left lower lobe, *LUL* = left upper lobe, *RLL* = right lower lobe, *RML* = right middle lobe, *RUL* = right upper lobe. **(C)** Bronchoscopic image obtained after BLVR shows an endobronchial valve in the anterior segmental bronchus (arrow). **(D, E)** Frontal chest radiograph **(D)** that was obtained subsequently and coronal CT image **(E)** show a successful outcome with right upper lobe collapse (white arrow) and endobronchial valves (black arrows).



geneity, and fissure integrity should be assessed visually, quantitative CT is more objective and reproducible (46).

The emphysema score is calculated in each lobe as the percentage of voxels less than –910 HU or less than –950 HU. The most commonly

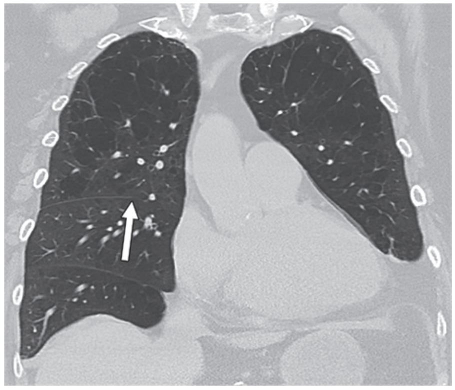


Figure 13. Severe emphysema in a 77-year-old man who presented for BLVR evaluation. Coronal CT image shows heterogeneous emphysema in the upper lobes but an incomplete minor fissure (arrow), disqualifying the right upper lobe as a potential target.

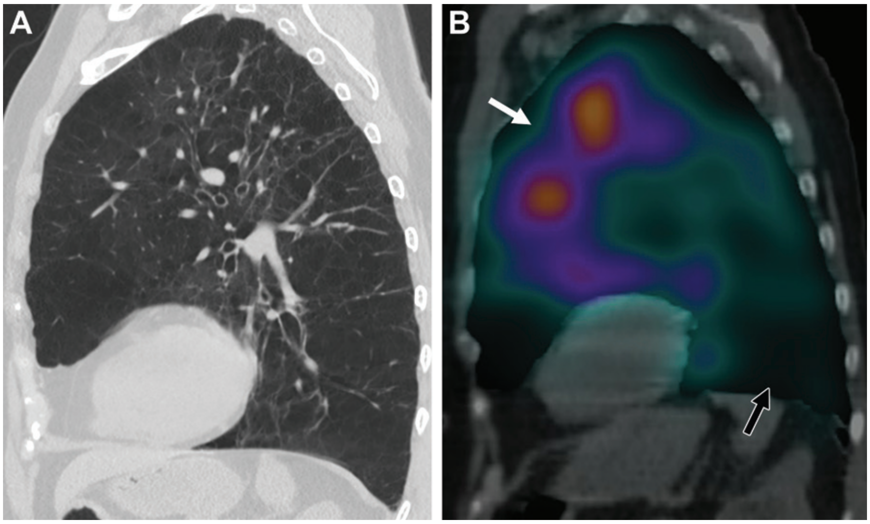


Figure 14. Severe emphysema in a 76-year-old woman who presented for BLVR evaluation. **(A)** Sagittal CT image shows homogeneous emphysema, with an emphysema score of 52% in the left upper lobe and 55% in the left lower lobe. **(B)** Sagittal perfusion SPECT/CT image shows better perfusion to the left upper lobe (white arrow). The left lower lobe (black arrow) was subsequently selected as the target lobe.

used threshold for thin-section scans is –950 HU, although both thresholds are reported. Target lobes have an emphysema score greater than 50% (47). Acute pulmonary findings such as pneumonia and edema falsely decrease the emphysema score, and repeat imaging may be needed.

The heterogeneity score refers to the difference in emphysema score between ipsilateral lobes (47). Although early trials showed clinical improvement in only patients with heterogeneous emphysema (heterogeneity score >15), subsequent studies with refined patient selection demonstrated benefit in patients with homogeneous emphysema (heterogeneity score <15) (40,42,48,49).

Incomplete fissures (fissure integrity <90%) allow collateral ventilation from adjacent lobes and reduce the likelihood of lobar collapse (47). While fissure integrity is calculated by using quantitative CT and ideally is greater than 90%, the fissures should be subjectively assessed for any defects to substantiate quantitative CT findings or resolve any potential discrepancies between different quantitative CT platforms. Coronal and sagittal CT reconstructions help identify fissure defects, which tend to be located medially toward the hila (Fig 13). The left major fissure is complete more frequently than the right fissures (50). In patients with an incomplete minor fissure, the right upper and middle lobes can be targeted simultaneously. Collateral ventilation can also be directly measured bronchoscopically with the Chartis System (Pulmonx), which is a proprietary balloon-tipped catheter that measures flow and pressure in the target lobe. Persistent flow after balloon occlusion confirms collateral ventilation.

Perfusion scintigraphy or SPECT/CT may help identify an optimal target lobe in patients with homogeneous emphysema or multiple potential targets (Fig 14). Patients with target lobe hypoperfusion or a well-perfused ipsilateral nontarget lobe show greater clinical improvement after BLVR than patients with good target lobe perfusion and poor ipsilateral perfusion (51,52). The major limitation of perfusion imaging is quantification by lung zones (upper, mid, and lower) rather than individual lobes. Software for semiautomatic SPECT/CT lobar quantification is available but not widespread.

At chest radiography, endobronchial valves are small umbrellalike structures with radiopaque

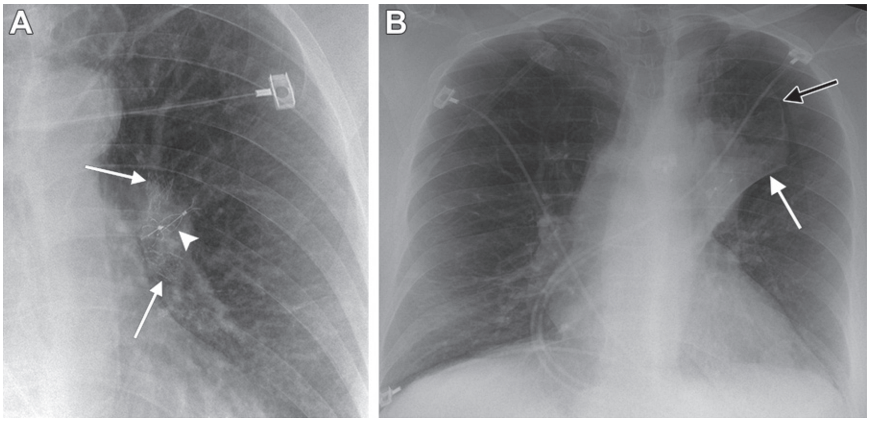


Figure 15. BLVR in a 65-year-old woman with severe emphysema. **(A)** Coned-down frontal chest radiograph obtained after the procedure with aeration of the left upper lobe shows the radiographic appearance of endobronchial valves: two Zephyr valves (Pulmonx) (arrows) and two overlapping Spiration valves (Olympus) (arrowhead). **(B)** Frontal chest radiograph obtained the following day shows the development of partial lobar collapse (white arrow) and a pneumothorax (black arrow). Two weeks later, the pneumothorax resolved and the left upper lobe was completely collapsed (not shown).

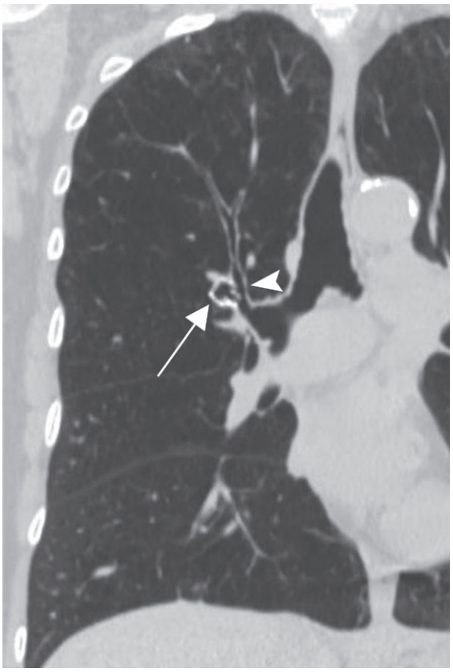


Figure 16. Placement of endobronchial valves in the right upper lobe in a 70-year-old woman. The lobe did not collapse and chest CT was performed. Coronal CT image shows distal migration of the posterior segmental valve into a lateral subsegmental bronchus (arrow), leaving a patent medial subsegmental branch (arrowhead).

struts located centrally within a lobe (Fig 15). Three to five valves are typically deployed per procedure. The goal of lobar collapse may take days to weeks. Pneumothorax is the most frequent adverse event after BLVR (up to 26.6% of cases) but does not affect the likelihood of lobar collapse or long-term clinical benefit (40,43,44,48,53) (Fig 15). The mechanism is thought to be rupture of subpleural blebs or bullae in nontreated lobes due to a rapid shift in lung volumes (42). Because most pneumothoraces occur within 3 days, hospitalization is recommended for a minimum of 72 hours after BLVR (40,53).

Collateral ventilation due to valve migration prevents lobar collapse. Subtle valve migration may not be appreciated at radiography but can be inferred at CT if the target lobe fails to collapse and all segments are not obstructed by a valve (Fig 16). The rate of valve migration or expectoration is 0.6%–7.2% (40,43,48). Other uncommon complications include pneumonia, hemoptysis, COPD exacerbation, and respiratory failure. Additional drawbacks of BLVR are the unavoidable collapse of some healthy lung tissue and inability to detect new lung nodules in the collapsed lobe, which remains at high risk for lung cancer.

Before BLVR, endobronchial valves were approved in 2008 for humanitarian use in patients with persistent air leak, blocking airflow and allowing the distal lung to heal (Fig 17). In a retrospective study of 40 patients, air leak completely resolved in 48% of patients and decreased in 45% of patients (54). Chest tubes can usually be removed after a few weeks followed by valve removal in 1–2 months (54).

Bronchial Thermoplasty

Bronchial thermoplasty (BT) is a nonpharmacologic treatment of severe uncontrolled asthma despite optimal medical treatment. Radiofrequency energy is delivered to the lobe through subsegmental bronchi over a series of bronchoscopic procedures with the goal of reducing smooth muscle mass and contractility.

RadioGraphics

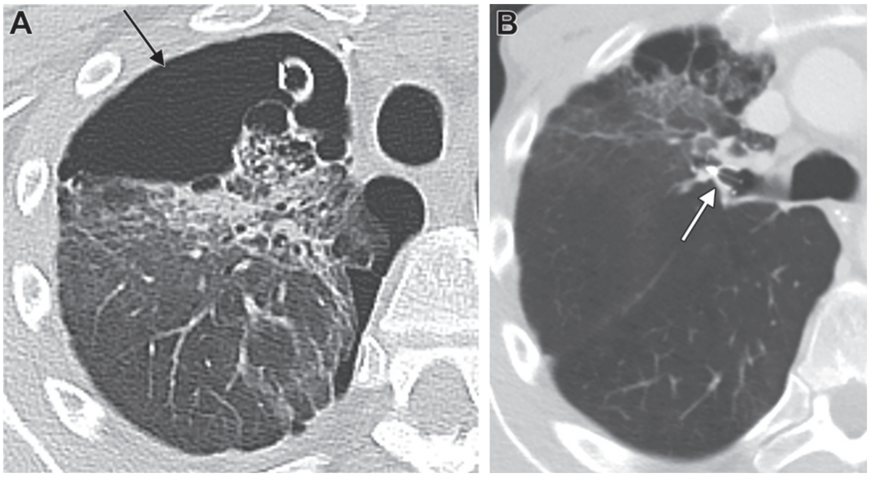


Figure 17. Prior pneumothorax and persistent air leak despite blebectomy and talc pleurodesis in a 31-year-old man. **(A)** Axial CT image shows a pneumothorax (arrow) with a chest tube in place. **(B)** Axial CT image acquired 3 months after placement of three endobronchial valves into the right upper lobe shows resolution of the pneumothorax. One of the endobronchial valves is depicted (arrow).

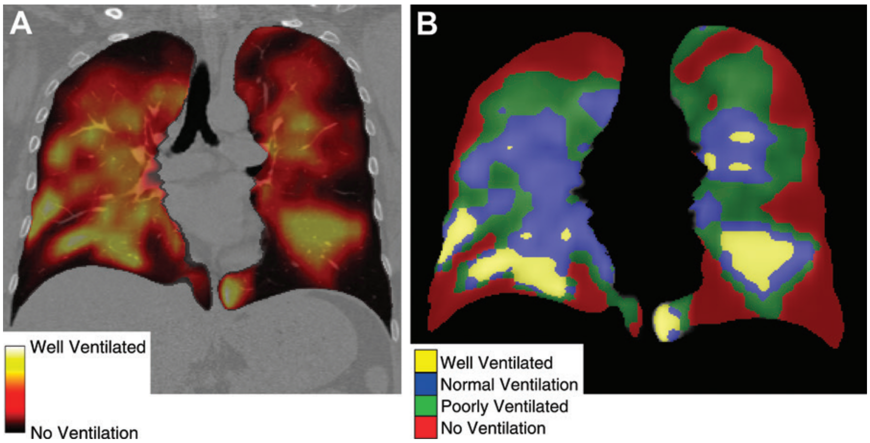


Figure 18. Severe uncontrolled asthma in a 33-year-old woman undergoing evaluation for BT. **(A)** Coronal ^{129}Xe MR image scored with ventilated volume percentage and registered to a prior CT image shows multiple segments of reduced ventilation. **(B)** Corresponding coronal color mask overlay segments the ventilation data into four tiers.

BT reduces corticosteroid usage, severe asthma exacerbations by 32%–45%, and emergency department visits by 55%–84% (55,56). The most common adverse event is temporary worsening of respiratory symptoms with an 8.4%–13.2% periprocedural risk of hospitalization over a set of three treatments (55,56).

The conventional approach treats the right lower lobe in the first session, left lower lobe in the second session, and both upper lobes in the third session. A recent prospective study evaluated hyperpolarized xenon-129 (^{129}Xe) MRI in guiding therapy to specific airways (Fig 18) (57). The most poorly ventilated regions were targeted during the first BT session, and the remaining airways were treated during the second and third sessions. The results showed that a single BT treatment guided by ^{129}Xe MRI provided similar short-term quality-of-life improvements as those of a standard three-session BT.

In patients with acute symptoms after BT, imaging abnormalities usually occur in the treated zones but have been reported in nontarget lobes. A prospective study of 12 patients found acute abnormalities on all 36 posttreatment CT images, with most resolving by 6 weeks (58). The most common finding was peribronchial consolidation or ground-glass opacities (94%), followed by partial bronchial occlusion (63%), atelectasis (38%), and bronchial dilatation (19%). Another study found septal thickening on 39% of images and pleural effusions on 68% of images (59).

Fiducial Marker Placement

Stereotactic body radiation therapy (SBRT) is an important option for patients with inoper-

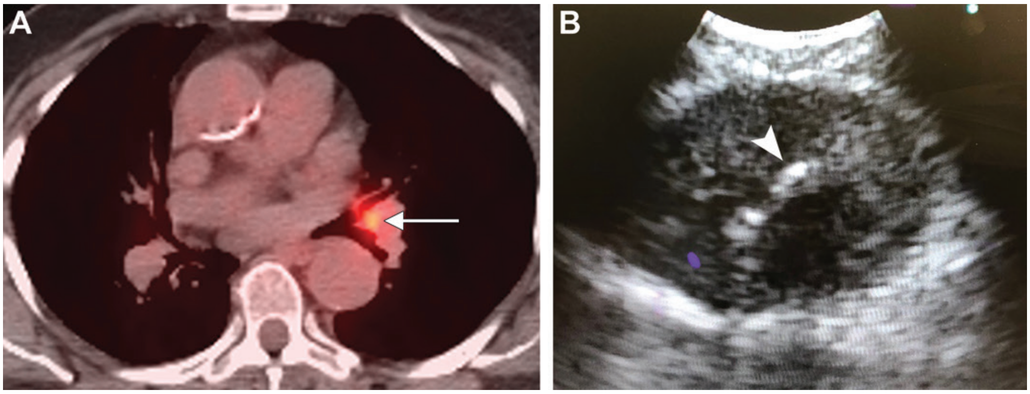


Figure 19. Fiducial marker for SBRT in an 82-year-old woman with lung cancer. **(A)** Axial fused PET/CT image shows a hypermetabolic left hilar lymph node (arrow). **(B)** Convex-probe EBUS image obtained for guidance shows a thin echogenic fiducial marker (arrowhead) that was placed into the lymph node.

able early-stage lung cancer. To synchronize SBRT tracking systems with respiratory variation, metallic fiducial markers (usually gold or platinum) are inserted into or adjacent to target lesions that are not visible at chest radiography (Fig 19). These include mediastinal and hilar lymph nodes, central lung cancers, and some peripheral nodules smaller than 20 mm (60,61). Convex-probe EBUS typically guides placement into central lesions, and ENB can be used for peripheral lesions.

Percutaneous Tracheostomy

Unlike surgical tracheostomy, percutaneous tracheostomy is performed at the bedside under bronchoscopic visualization, and therefore it is an attractive option in patients with critical illness (3). Unfavorable anatomy, such as in patients with obesity without palpable midline structures, is the main barrier to percutaneous tracheostomy. A meta-analysis comparing percutaneous and surgical approaches showed decreased rates of wound infection and increased likelihood of mucus plugging and accidental dislodgement with percutaneous tracheostomy but otherwise no clear safety difference (62). Other potential early complications of percutaneous tracheostomy include bleeding, subcutaneous emphysema, and false lumen insertion. Tracheo-innominate fistula is the most feared complication but is extremely rare (63). Percutaneous and surgical tracheostomy tubes are indistinguishable at imaging.

Pleural Interventions

Medical thoracoscopy, or pleuroscopy, is a less invasive alternative to surgical thoracoscopy and thoracotomy. It can be performed under moderate sedation in an ambulatory setting and offers a diagnostic efficiency of 93.3% (64). It should be considered when thoracentesis and closed pleural biopsy cannot help establish a diagnosis for an exudative pleural effusion.

Chemical pleurodesis and indwelling pleural catheters (IPCs) are the main palliative treatment options for symptomatic and recurrent malignant pleural effusions. Instillation of sterile talc, the sclerosant of choice for chemical pleurodesis, into the pleural space causes an inflammatory reaction, resulting in pleural adhesions that prevent reaccumulation of pleural fluid in about 75% of cases (65). Talc pleurodesis is not recommended in cases of trapped lung. Pain is the most common side effect, and patients may be hospitalized for several days while undergoing suction. CT images show high-attenuation pleural accumulations of talc, which may be hypermetabolic at PET because of pleural inflammation (Fig 20). Ipsilateral reexpansion and pneumonitis are potential imaging complications (66).

Compared with talc pleurodesis, IPCs offer better symptom control and shorter hospitalization time without significantly affecting complication rates or mortality (67). Patients typically drain their IPCs two to three times per week at home. Some IPCs can be removed after spontaneous pleurodesis, which may take several months. A rapid pleurodesis protocol combines medical thoracoscopy with talc instillation and simultaneous IPC placement, reducing hospital stay and IPC duration (68). IPCs can also be used in refractory nonmalignant pleural effusions due to heart failure or cirrhosis. IPC-related pleural infection occurs in about 3.7% of patients (69). Other potential complications include pneumothorax, catheter tract metastases, and cellulitis.

Typical radiographic findings after IPC placement are decreased pleural fluid and reexpansion pulmonary edema. Pneumothorax is the main complication. Occasionally, the

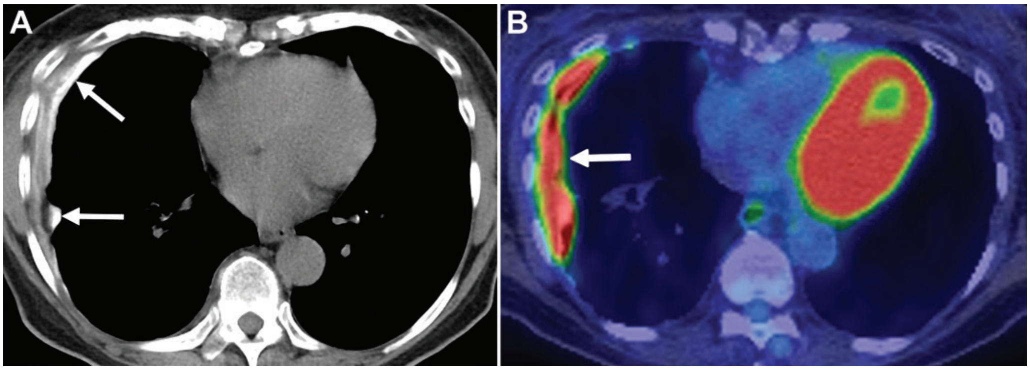


Figure 20. Metastatic non–small cell lung cancer and malignant right pleural effusion in a 73-year-old woman after talc pleurodesis. **(A)** Axial noncontrast CT image shows high attenuation lining the right pleural space (arrows). **(B)** Axial fused PET/CT image shows diffusely increased uptake (arrow).

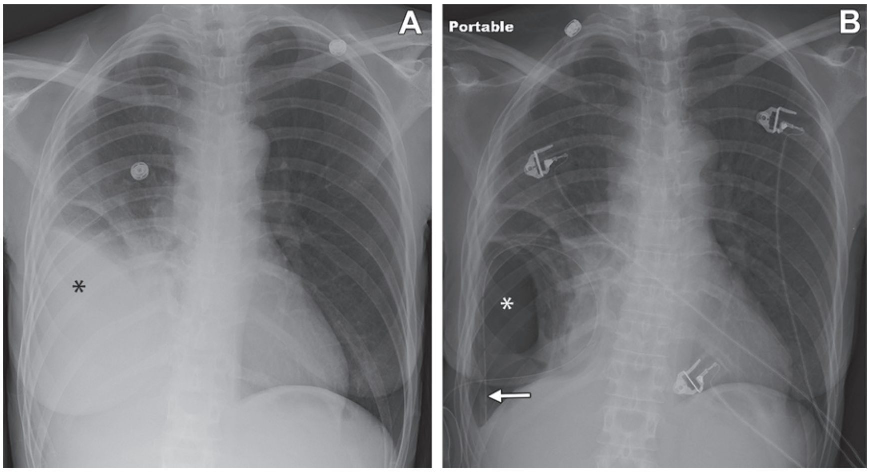


Figure 21. IPC placement in a 66-year-old woman with metastatic renal cell carcinoma. **(A)** Frontal chest radiograph shows a mildly loculated right pleural effusion (*). An IPC was then placed for a refractory malignant pleural effusion. **(B)** Frontal chest radiograph obtained after the procedure shows the IPC (arrow) and loculated pleural gas conforming to the space that was previously occupied by the pleural effusion (*). There is no lung re-expansion.

ipsilateral lung cannot re-expand because of CAO or visceral pleural scarring (trapped lung) or tumor (lung entrapment). Lung volume remains unchanged, and loculated gas conforms to the space that was previously occupied by the pleural effusion (Fig 21). Unlike pneumothorax due to air leak, no specific management is indicated. Visceral pleural thickening at CT may help differentiate the two.

Other Evolving Techniques

Robotic-assisted Bronchoscopy

Robotic-assisted bronchoscopy improves diagnostic accuracy through continuous direct visualization and precise instrument control. Although available data are largely from cadaveric studies, recent live human studies have demonstrated excellent lesion localization and safety (70).

Bronchoscopic Transparenchymal Nodule Access

In bronchoscopic transparenchymal nodule access (BTPNA), a biopsy needle is advanced across a bronchial wall and through lung parenchyma to a target lesion, eliminating the need for a direct path through an airway. In the first in-human feasibility study, BTPNA was successful in 10 of 12 patients. A diagnosis was made in all 10 patients with no significant adverse events despite needle paths equal to or greater than 50 mm in seven patients (71).

Transbronchial Cryobiopsy

Transbronchial cryobiopsy is a potential alternative to surgical lung biopsy, which is the current reference standard in the diagnosis of diffuse parenchymal lung disease. A cryoprobe is extended into the lung periphery, cooled for a few seconds, and then removed along with adherent tissue (3).

The resulting biopsy specimens are larger than standard bronchoscopic biopsy specimens and without significant crush artifact. Although transbronchial cryobiopsy currently has an overall lower diagnostic yield than surgical lung biopsy, it offers similar confidence in diagnosing idiopathic pulmonary fibrosis within the context of multidisciplinary discussion (72,73).

Ablation of Early-Stage Cancers

Endobronchial ablation of early-stage lung cancer or oligometastases from distal cancer is in consideration for a clinical trial as an alternative treatment in patients who are not candidates for surgery. The main advantage is the ability to deliver enough energy to treat the tumor directly while sparing more lung parenchyma than is achievable with external radiation (74).

Endobronchial Intratumoral Chemotherapy

Endobronchial intratumoral chemotherapy is a potential alternative to stent placement in patients with malignant CAO. A recent pilot study found that a microneedle injection of paclitaxel after airway recanalization was both feasible and safe in patients with non–small cell lung cancer (75).

Conclusion

Interventional pulmonology has transformed the approach to thoracic disease with new diagnostic procedures, minimally invasive alternatives to surgery, rapid relief of CAO, and nonpharmacologic therapies for COPD and asthma. The field continues to grow and evolve, with many recent innovations and new ones on the horizon. As availability increases and indications expand, radiologists must be familiar with core interventional pulmonology procedures and the important aspects of pre- and postprocedure imaging.

***Disclosures of Conflicts of Interest.*—M.C.** *Activities related to the present article:* disclosed no relevant relationships. *Activities not related to the present article:* consultant to Novartis, Sanofi, Teva, and Genentech; institution received grants from AstraZeneca, GlaxoSmithKline, Novartis, Pulmatrix, Sanofi, and Shionogi; lectured for AstraZeneca, Genentech, GlaxoSmithKline, Regeneron, Sanofi, and Teva; receives royalties from Elsevier. *Other activities:* disclosed no relevant relationships.

References

1. Mullon JJ, Burkart KM, Silvestri G, et al. Interventional Pulmonology Fellowship Accreditation Standards: Executive Summary of the Multisociety Interventional Pulmonology Fellowship Accreditation Committee. Chest 2017;151(5):1114–1121.
2. AABIP/AIPPD Interventional Pulmonology Fellowship Accreditation. https://aabronchology.org/education/fellowships/aabipaippd-interventional-pulmonology-fellowship-accreditation-application-and-process. Accessed March 1, 2021.
3. Wahidi MM, Herth FJF, Chen A, Cheng G, Yarmus L. State of the Art: Interventional Pulmonology. Chest 2020;157(3):724–736.
4. Zöllner F. Gustav Killian, father of bronchoscopy. Arch Otolaryngol 1965;82(6):656–659.
5. Ikeda S, Yanai N, Ishikawa S. Flexible bronchofiberscope. Keio J Med 1968;17(1):1–16.
6. Yasufuku K, Nakajima T, Motoori K, et al. Comparison of endobronchial ultrasound, positron emission tomography, and CT for lymph node staging of lung cancer. Chest 2006;130(3):710–718.
7. Silvestri GA, Gonzalez AV, Jantz MA, et al. Methods for staging non-small cell lung cancer: Diagnosis and management of lung cancer, 3rd ed: American College of Chest Physicians evidence-based clinical practice guidelines. Chest 2013;143(5 Suppl):e211S–e250S.
8. Herth F, Ernst A, Schulz M, Becker H. Endobronchial ultrasound reliably differentiates between airway infiltration and compression by tumor. Chest 2003;123(2):458–462.
9. Oki M, Saka H, Asano F, et al. Use of an ultrathin vs thin bronchoscope for peripheral pulmonary lesions: a randomized trial. Chest 2019;156(5):954–964.
10. Folch EE, Pritchett MA, Nead MA, et al. Electromagnetic navigation bronchoscopy for peripheral pulmonary lesions: one-year results of the prospective, multicenter NAVIGATE study. J Thorac Oncol 2019;14(3):445–458.
11. Gex G, Pralong JA, Combescure C, Seijo L, Rochat T, Soccal PM. Diagnostic yield and safety of electromagnetic navigation bronchoscopy for lung nodules: a systematic review and meta-analysis. Respiration 2014;87(2):165–176.
12. Zhang W, Chen S, Dong X, Lei P. Meta-analysis of the diagnostic yield and safety of electromagnetic navigation bronchoscopy for lung nodules. J Thorac Dis 2015;7(5):799–809.
13. Seijo LM, de Torres JP, Lozano MD, et al. Diagnostic yield of electromagnetic navigation bronchoscopy is highly dependent on the presence of a Bronchus sign on CT imaging: results from a prospective study. Chest 2010;138(6):1316–1321.
14. Aboudara M, Roller L, Rickman O, et al. Improved diagnostic yield for lung nodules with digital tomosynthesis-corrected navigational bronchoscopy: Initial experience with a novel adjunct. Respirology 2020;25(2):206–213.
15. Pritchett MA, Schampaert S, de Groot JAH, Schirmer CC, van der Bom I. Cone-beam CT with augmented fluoroscopy combined with electromagnetic navigation bronchoscopy for biopsy of pulmonary nodules. J Bronchology Interv Pulmonol 2018;25(4):274–282.
16. Casal RF, Sarkiss M, Jones AK, et al. Cone beam computed tomography-guided thin/ultrathin bronchoscopy for diagnosis of peripheral lung nodules: a prospective pilot study. J Thorac Dis 2018;10(12):6950–6959.
17. Kheir F, Thakore SR, Uribe Becerra JP, et al. Cone-Beam Computed Tomography-Guided Electromagnetic Navigation for Peripheral Lung Nodules. Respiration 2021;100(1):44–51.
18. Wiener RS, Schwartz LM, Woloshin S, Welch HG. Population-based risk for complications after transthoracic needle lung biopsy of a pulmonary nodule: an analysis of discharge records. Ann Intern Med 2011;155(3):137–144.
19. Ost DE, Ernst A, Grosu HB, et al. Therapeutic bronchoscopy for malignant central airway obstruction: success rates and impact on dyspnea and quality of life. Chest 2015;147(5):1282–1298.
20. Ost DE, Ernst A, Grosu HB, et al. Complications Following Therapeutic Bronchoscopy for Malignant Central Airway Obstruction: Results of the AQuIRE Registry. Chest 2015;148(2):450–471.
21. Ernst A, Simoff M, Ost D, Goldman Y, Herth FJF. Prospective risk-adjusted morbidity and mortality outcome analysis after therapeutic bronchoscopic procedures: results of a multi-institutional outcomes database. Chest 2008;134(3):514–519.
22. Giovacchini CX, Kessler ER, Merrick CM, et al. Clinical and radiographic predictors of successful therapeutic bronchoscopy for the relief of malignant central airway obstruction. BMC Pulm Med 2019;19(1):219.

RadioGraphics

23. Baroni RH, Feller-Kopman D, Nishino M, et al. Tracheobronchomalacia: comparison between end-expiratory and dynamic expiratory CT for evaluation of central airway collapse. Radiology 2005;235(2):635–641.
24. Vishwanath G, Madan K, Bal A, Aggarwal AN, Gupta D, Agarwal R. Rigid bronchoscopy and mechanical debulking in the management of central airway tumors: an Indian experience. J Bronchology Interv Pulmonol 2013;20(2):127–133.
25. Wahidi MM, Unroe MA, Adlakha N, Beyea M, Shofer SL. The use of electrocautery as the primary ablation modality for malignant and benign airway obstruction. J Thorac Oncol 2011;6(9):1516–1520.
26. Crosta C, Spaggiari L, De Stefano A, Fiori G, Ravizza D, Pastorino U. Endoscopic argon plasma coagulation for palliative treatment of malignant airway obstructions: early results in 47 cases. Lung Cancer 2001;33(1):75–80.
27. Reddy C, Majid A, Michaud G, et al. Gas embolism following bronchoscopic argon plasma coagulation: a case series. Chest 2008;134(5):1066–1069.
28. Schumann C, Hetzel M, Babiak AJ, et al. Endobronchial tumor debulking with a flexible cryoprobe for immediate treatment of malignant stenosis. J Thorac Cardiovasc Surg 2010;139(4):997–1000.
29. Langendijk H, de Jong J, Tjwa M, et al. External irradiation versus external irradiation plus endobronchial brachytherapy in inoperable non-small cell lung cancer: a prospective randomized study. Radiother Oncol 2001; 58(3):257–268.
30. Reveiz L, Rueda JR, Cardona AF. Palliative endobronchial brachytherapy for non-small cell lung cancer. Cochrane Database Syst Rev 2012;12:CD004284.
31. Stewart A, Parashar B, Patel M, et al. American Brachytherapy Society consensus guidelines for thoracic brachytherapy for lung cancer. Brachytherapy 2016;15(1):1–11.
32. Flannery A, Daneshvar C, Dutau H, Breen D. The art of rigid bronchoscopy and airway stenting. Clin Chest Med 2018;39(1):149–167.
33. Dumon JF, Cavaliere S, Diaz-Jimenez JP. Seven-year experience with the Dumon prosthesis. J Bronchol Interv Pulmonol 1996;3(1):6–10.
34. Saad CP, Murthy S, Krizmanich G, Mehta AC. Self-expandable metallic airway stents and flexible bronchoscopy: long-term outcomes analysis. Chest 2003;124(5):1993–1999.
35. Sheski FD, Mathur PN. Long-term results of fiberoptic bronchoscopic balloon dilation in the management of benign tracheobronchial stenosis. Chest 1998;114(3):796–800.
36. Liang W, Hu P, Guo W, Su Z, Li J, Li S. Appropriate treatment sessions of flexible bronchoscopic balloon dilation for patients with nonmalignant central airway stenosis. Ther Adv Respir Dis 2019;13:1753466619831966.
37. Shitrit D, Kuchuk M, Zismanov V, Rahman NA, Amital A, Kramer MR. Bronchoscopic balloon dilatation of tracheobronchial stenosis: long-term follow-up. Eur J Cardiothorac Surg 2010;38(2):198–202.
38. Hautmann H, Gamarra F, Pfeifer KJ, Huber RM. Fiberoptic bronchoscopic balloon dilatation in malignant tracheobronchial disease: indications and results. Chest 2001;120(1):43–49.
39. Mayse ML, Greenheck J, Friedman M, Kovitz KL. Successful bronchoscopic balloon dilation of nonmalignant tracheobronchial obstruction without fluoroscopy. Chest 2004;126(2):634–637.
40. Sciurba FC, Ernst A, Herth FJ, et al. A randomized study of endobronchial valves for advanced emphysema. N Engl J Med 2010;363(13):1233–1244.
41. Davey C, Zoumot Z, Jordan S, et al. Bronchoscopic lung volume reduction with endobronchial valves for patients with heterogeneous emphysema and intact interlobar fissures (the BeLieVeR-HIFi study): a randomised controlled trial. Lancet 2015;386(9998):1066–1073.
42. Valipour A, Slebos DJ, Herth F, et al. Endobronchial Valve Therapy in Patients with Homogeneous Emphysema. Results from the IMPACT Study. Am J Respir Crit Care Med 2016;194(9):1073–1082.
43. Criner GJ, Sue R, Wright S, et al. A Multicenter Randomized Controlled Trial of Zephyr Endobronchial Valve Treatment in Heterogeneous Emphysema (LIBERATE). Am J Respir Crit Care Med 2018;198(9):1151–1164.
44. Criner GJ, Delage A, Voelker K, et al. Improving Lung Function in Severe Heterogenous Emphysema with the Spiration Valve System (EMPROVE): A Multicenter, Open-Label Randomized Controlled Clinical Trial. Am J Respir Crit Care Med 2019;200(11):1354–1362.
45. Fishman A, Martinez F, Naunheim K, et al. A randomized trial comparing lung-volume-reduction surgery with medical therapy for severe emphysema. N Engl J Med 2003;348(21):2059–2073.
46. Fiorelli A, Poggi C, Anile M, et al. Visual analysis versus quantitative CT analysis of interlobar fissure integrity in selecting emphysematous patients for endobronchial valve treatment. Interact Cardiovasc Thorac Surg 2019;28(5):751–759.
47. Schuhmann M, Raffy P, Yin Y, et al. Computed tomography predictors of response to endobronchial valve lung reduction treatment. Comparison with Chartis. Am J Respir Crit Care Med 2015;191(7):767–774.
48. Herth FJ, Noppen M, Valipour A, et al. Efficacy predictors of lung volume reduction with Zephyr valves in a European cohort. Eur Respir J 2012;39(6):1334–1342.
49. Klooster K, ten Hacken NH, Hartman JE, Kerstjens HA, van Rikxoort EM, Slebos DJ. Endobronchial Valves for Emphysema without Interlobar Collateral Ventilation. N Engl J Med 2015;373(24):2325–2335.
50. Lee SW, Shin SY, Park TS, et al. Clinical Utility of Quantitative CT Analysis for Fissure Completeness in Bronchoscopic Lung Volume Reduction: Comparison between CT and Chartis™. Korean J Radiol 2019;20(7):1216–1225.
51. Argula RG, Strange C, Ramakrishnan V, Goldin J. Baseline regional perfusion impacts exercise response to endobronchial valve therapy in advanced pulmonary emphysema. Chest 2013;144(5):1578–1586.
52. Thomsen C, Theilig D, Herzog D, et al. Lung perfusion and emphysema distribution affect the outcome of endobronchial valve therapy. Int J Chron Obstruct Pulmon Dis 2016;11:1245–1259.
53. Gompelmann D, Benjamin N, Kontogianni K, et al. Clinical and radiological outcome following pneumothorax after endoscopic lung volume reduction with valves. Int J Chron Obstruct Pulmon Dis 2016;11:3093–3099.
54. Travaline JM, McKenna RJ Jr, De Giacomo T, et al. Treatment of persistent pulmonary air leaks using endobronchial valves. Chest 2009;136(2):355–360.
55. Castro M, Rubin AS, Laviolette M, et al. Effectiveness and safety of bronchial thermoplasty in the treatment of severe asthma: a multicenter, randomized, double-blind, sham-controlled clinical trial. Am J Respir Crit Care Med 2010;181(2):116–124.
56. Chupp G, Laviolette M, Cohn L, et al. Long-term outcomes of bronchial thermoplasty in subjects with severe asthma: a comparison of 3-year follow-up results from two prospective multicentre studies. Eur Respir J 2017;50(2):1700017 [Published correction appears in Eur Respir J 2017;50(4):1750017.].
57. Hall CS, Quirk JD, Goss CW, et al. Single-Session Bronchial Thermoplasty Guided by ^{129}Xe Magnetic Resonance Imaging. A Pilot Randomized Controlled Clinical Trial. Am J Respir Crit Care Med 2020;202(4):524–534.
58. d'Hooghe JNS, van den Berk IAH, Annema JT, Bonta PI. Acute Radiological Abnormalities after Bronchial Thermoplasty: A Prospective Cohort Trial. Respiration 2017;94(3):258–262.
59. Debray MP, Dombret MC, Pretolani M, et al. Early computed tomography modifications following bronchial thermoplasty in patients with severe asthma. Eur Respir J 2017;49(3):1601565.
60. Pishvaian AC, Collins B, Gagnon G, Ahlawat S, Haddad NG. EUS-guided fiducial placement for CyberKnife radiotherapy of mediastinal and abdominal malignancies. Gastrointest Endosc 2006;64(3):412–417.
61. Lachkar S, Guisier F, Roger M, et al. Assessment of Per-Endoscopic Placement of Fiducial Gold Markers for Small Peripheral Lung Nodules < 20 mm Before Stereotactic Radiation Therapy. Chest 2018;153(2):387–394.
62. Higgins KM, Punthakee X. Meta-analysis comparison of open versus percutaneous tracheostomy. Laryngoscope 2007;117(3):447–454.

63. Lerner AD, Yarmus L. Percutaneous Dilational Tracheostomy. Clin Chest Med 2018;39(1):211–222.
64. Blanc FX, Atassi K, Bignon J, Housset B. Diagnostic value of medical thoracoscopy in pleural disease: a 6-year retrospective study. Chest 2002;121(5):1677–1683.
65. Stefani A, Natali P, Casali C, Morandi U. Talc poudrage versus talc slurry in the treatment of malignant pleural effusion: A prospective comparative study. Eur J Cardiothorac Surg 2006;30(6):827–832.
66. Kim Y, Kim YK, Choi MY, Lee KE. A case of acute pneumonitis following talc pleurodesis: high-resolution CT findings. J Thorac Imaging 2006;21(1):47–49.
67. Davies HE, Mishra EK, Kahan BC, et al. Effect of an indwelling pleural catheter vs chest tube and talc pleurodesis for relieving dyspnea in patients with malignant pleural effusion: the TIME2 randomized controlled trial. JAMA 2012;307(22):2383–2389.
68. Reddy C, Ernst A, Lamb C, Feller-Kopman D. Rapid pleurodesis for malignant pleural effusions: a pilot study. Chest 2011;139(6):1419–1423.
69. Bibby AC, Clive AO, Slade GC, et al. Survival in Patients With Malignant Pleural Effusions Who Developed Pleural Infection: A Retrospective Case Review From Six UK Centers. Chest 2015;148(1):235–241.
70. Chen AC, Pastis NJ Jr, Mahajan AK, et al. Robotic Bronchoscopy for Peripheral Pulmonary Lesions: A Multicenter Pilot and Feasibility Study (BENEFIT). Chest 2021;159(2):845–852.
71. Herth FJ, Eberhardt R, Sterman D, Silvestri GA, Hoffmann H, Shah PL. Bronchoscopic transparenchymal nodule access (BTPNA): first in human trial of a novel procedure for sampling solitary pulmonary nodules. Thorax 2015;70(4):326–332.
72. Maldonado F, Danoff SK, Wells AU, et al. Transbronchial Cryobiopsy for the Diagnosis of Interstitial Lung Diseases: CHEST Guideline and Expert Panel Report. Chest 2020;157(4):1030–1042.
73. Tomassetti S, Ravaglia C, Wells AU, et al. Prognostic value of transbronchial lung cryobiopsy for the multidisciplinary diagnosis of idiopathic pulmonary fibrosis: a retrospective validation study. Lancet Respir Med 2020;8(8):786–794.
74. Tanabe T, Koizumi T, Tsushima K, et al. Comparative study of three different catheters for CT imaging-bronchoscopy-guided radiofrequency ablation as a potential and novel interventional therapy for lung cancer. Chest 2010;137(4):890–897.
75. Yarmus L, Mallow C, Akulian J, et al. Prospective Multicentered Safety and Feasibility Pilot for Endobronchial Intratumoral Chemotherapy. Chest 2019;156(3):562–570.