Review Article

Digital tomosynthesis for navigational bronchoscopy: a clinical practice review

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Abstract: Pulmonary nodules, defined as single opacities up to 30 mm within normal lung tissue, are more frequently detected as a result of enhanced lung cancer screening methods utilizing low-dose computed tomography (LDCT), which has significantly reduced the mortality rate of lung cancer. The National Lung Screening Trial (NLST) highlighted that 39% of participants exhibited nodules, with a substantial proportion requiring further evaluation. The United States Preventive Services Task Force (USPSTF) has since recommended routine LDCT screening for high-risk individuals. Traditionally, lung nodule evaluation relied on risk prediction calculators, guiding management through serial imaging or biopsies. Computed tomography (CT)-guided transthoracic needle biopsy (TTNB) has been the gold standard for minimally invasive biopsy. However, its limitations include higher complication rates, especially for smaller and more central nodules. Navigational bronchoscopy (NB) offers a safer alternative, enabling the assessment of multiple nodules in one session along with concomitant mediastinal and hilar lymph node evaluation utilizing endobronchial ultrasound (EBUS). One of the challenges of bronchoscopic biopsy of lung nodules has been CT-body divergence, limiting diagnostic yield and accuracy. In order to combat this challenge, recent advancements in NB technology, particularly the integration of digital tomosynthesis (DT), enhance procedural visualization and has been shown to improve diagnostic yield. This clinical practice review emphasizes the significance of optimizing intraoperative ventilator techniques as well as integrating enhanced imaging modalities like DT and cone beam CT (CBCT) in order to overcome CT-body divergence and subsequently improving localization and biopsy outcomes. Preliminary studies indicate promising diagnostic yields by integrating these advanced imaging technologies. Ongoing research is essential to refine these approaches and improve patient outcomes in lung nodule management.

Keywords: Bronchoscopy; digital tomosynthesis (DT); cone beam computed tomography (CBCT)

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Introduction

A pulmonary nodule is a single, clearly defined opacity up to 30 mm in diameter, found within normal lung tissue, without associated atelectasis, hilar enlargement or pleural effusion (1). These lesions may be solid, subsolid, or ground-glass in appearance. Lung nodule management has become ubiquitous, in part due to the results of the National Lung Screening Trial (NLST) (2). This study involving over 53,000 participants, showed that low-dose computed tomography (LDCT) scans reduced mortality by 20% compared to standard chest X-rays. Lung nodules were found in 39% of participants, with 72% requiring further evaluation (3). Nodules over 20 mm had a high risk

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of malignancy. This led to a grade B recommendation from the United States Preventive Services Task Force (USPSTF) for CT screening in high-risk individuals in 2013, which was later updated in 2021 to include those aged 50 to 80 years with a smoking history of at least 20 pack-years, including those who have quit within the previous 15 years. The evaluation of lung nodules typically begins with a lung cancer risk prediction calculator to assess the likelihood of malignancy. Based on the risk score, management options may include serial CT follow-ups, positron emission tomography (PET)-CT, nonsurgical biopsy, or surgical resection. Follow-up guidelines from the American College of Chest Physicians (ACCP) and the National Comprehensive Cancer Network (NCCN) recommend using minimally invasive methods for tissue sampling in lung cancer assessments (4,5). Nonsurgical biopsy options include CT-guided transthoracic needle biopsy (TTNB) and bronchoscopic biopsy. Historically, the gold standard for minimally invasive lung nodule biopsy has been CT-guided TTNB with an estimated diagnostic yield of 90%, though nodules <15 mm have reported yield of 60% to 80% (6-8). However, this is restricted to peripheral lesions and has a higher complication rate including pneumothorax (reported to be 12% to 45% with up to 2–15% requiring chest tube placement) and pulmonary hemorrhage (4% to 27%) (9). Navigational bronchoscopy (NB) is a minimally invasive alternative that allows for simultaneous sampling of multiple lung nodules, as well as mediastinal and hilar lymph nodes in a single session with a favorable safety profile, however, its diagnostic yield has traditionally been lower than that of CT-guided methods. A recent multicenter randomized controlled study showed that NB was noninferior to CT-TTNB for diagnosis of lung nodules, with a better safety profile (10). The success of NB can be attributed largely in part to improvement in proceduralists' ability to visualize the lesion during sampling. This clinical practice review highlights recent advancements in digital tomosynthesis (DT) NB technology which have been found to improve intraoperative lung nodule visualization as well as diagnostic yield.

DT

Planar radiography converts a three-dimensional (3D) volume into a two-dimensional (2D) image, causing tissue overlap that diminishes visibility and contrast. In 1921, Ziedses des Plantes proposed a tomographic method to eliminate out-of-plane structures (11). Conventional tomography enhances image quality at a specific depth but blurs other areas due to parallax. Ziedses des Plantes also theorized that multiple tomographic scans could be obtained from a single low-dose image, though the technology for this did not develop until the early 21st century (11).

From the 1960s to the 1980s, innovations like fluoroscopy improved acquisition techniques. While the shift from analog to digital methods simplified geometric tomography, the rise of CT in the late 1970s diverted attention from these advancements. It was not until the late 1990s, with decreased computing costs and the advent of high-quality flat panel detectors, that Ziedses des Plantes' concepts became viable for practical application.

Today, this technology is known as DT, enabling the reconstruction of multiple coronal image planes from a series of low-dose projections taken at limited angles with a stationary detector. In bronchoscopy, DT employs computer-based image processing algorithms to convert 2D images from a conventional C-arm, typically rotating between 50 to 70 degrees (compared to conventional CT where images are obtained over 180 to 360 degrees), into 3D reconstructions with a limited depth of field. Images are reconstructed using an algorithm that blurs the planes above and below the focal plane. A 50° sweep angle produces a 1 mm section thickness, with blurring occurring beyond 0.5 mm from the focal plane. Structures near the center of rotation have fewer motion artifacts and are clearer than those at the image periphery, which limits the ability to distinguish spatial relationships at the edges (12). A narrower angulation range requires fewer images, reducing radiation dose, but also provides less data for reconstruction. Recent advancements in artificial intelligence (AI) and machine learning have enabled modern DT systems to generate CT-like multi-axial images from limited inputs. Various bronchoscopic platforms incorporate DT technology.

Intraprocedural factors affecting diagnostic yield

Despite technological advancements, clinicians have identified CT-body-divergence (CTBD) and atelectasis as significant factors affecting the diagnostic yield in guided bronchoscopy (13). Navigational platforms, whether robotic assisted or using virtual navigation, rely on a virtual airway map created from a pre-procedural CT scan to locate target lesions. This preprocedural CT scan is

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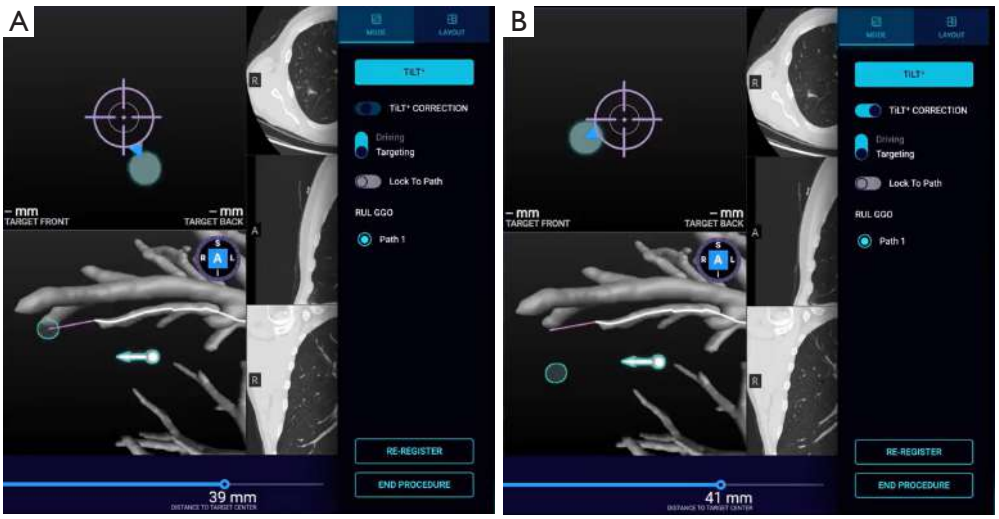


Figure 1 Tool-in-lesion. (A) Location of nodule in relation to the bronchoscope based on patient's preoperative CT scan. (B) Location of nodule in relation to the bronchoscope after fluoroscopy using Galaxy's TiLT+ technology that provides integrated DT. These two images highlight the importance of correcting for CT-to-body divergence. CT, computed tomography; DT, digital tomosynthesis; TiLT, tool-in-lesion tomosynthesis.

ideally performed at total lung capacity, which cannot be reproduced intraoperatively. The discrepancies between expected and real-time lesion locations—due to changes in lung anatomy—can lead to errors, known as CT-to-body divergence. This issue can lower diagnostic accuracy, extend procedure times, and complicate the operator's task. Factors contributing to this divergence include variations in lung volume, the time between the CT scan and the procedure, and changes in nodule size or other anatomical distortions.

Respiratory motion poses a significant challenge in biopsies, as peripheral nodules can move up to 17.6 mm between full inspiration and expiration, with some lower lobe lesions shifting over 60 mm (14). This movement is linked to a reduced diagnostic yield for lower lobe nodules, indicating that their spatial position changes throughout the respiratory cycle (15).

Atelectasis also impacts diagnostic yield, occurring rapidly after general anesthesia, particularly in the lower lobes. Causes include prolonged intubation, poor ventilation techniques, high oxygen levels leading to absorption atelectasis, and bronchoscope wedging (13). The dynamic changes in airway structure during the procedure can further misalign the actual anatomy from the original virtual map, increasing the risk of pneumothorax due to reduced distance between the lesion and the pleura. Moreover, atelectatic lung can resemble lung lesions on radial endobronchial ultrasound (EBUS) because it has a higher density than aerated lung (13). DT provides real-time 3D imaging during the procedure, allowing for a more accurate localization of target lesion, ameliorating the CT-to-body divergence as shown in *Figure 1*.

Anesthesia considerations for NB

Preprocedural considerations

Preprocedural incentive spirometry is advised to help recruit lung volume and prevent atelectasis (16). The maximum value achieved during spirometry can help the anesthesiologist gauge potential risks associated with higher tidal volumes used during the procedure. This is particularly crucial for patients at greater risk of atelectasis, including those who are obese or have lesions in the lower lung regions.

Pre-oxygenation before anesthetic induction and intubation is beneficial, but nitrogen washout during this process can lead to gas loss from the lungs, causing alveolar collapse and absorption atelectasis (17,18). Since using 100% oxygen is a significant contributor to atelectasis, it is recommended to use the lowest tolerable fraction of inspired oxygen (FiO_2) during pre-oxygenation, guided by oxygen saturation (17). It has been shown that an FiO_2 of 0.6 to 0.8 is associated with minimal atelectasis compared to FiO_2 of 1.0 (19). If reducing FiO_2 below 1.0 is not feasible

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during pre-induction, it should be kept at the lowest level once the endotracheal tube (ETT) is in place, with recruitment maneuvers performed using this lower FiO_2, maintained throughout the procedure as tolerated.

NB is typically performed using general anesthesia using ETT with paralysis to keep the patient completely still and allow for intermittent breath holds to optimize critical moments of navigation and biopsy. Using the largest possible ETT allows for better gas passage around the bronchoscope and minimizes circuit pressure increases (20). ETTs are preferred over laryngeal masks (LMAs) due to their ability to handle higher airway pressures and reduce the risk of aspiration and gastric insufflation, although this risk is still low (21). After the bronchoscopy, the ETT can be replaced with an LMA for complete EBUS staging in smaller patients if a good seal is achieved. The ventilatory strategy to prevent atelectasis (VESPA) trial compared two ventilation strategies: standard ventilation with an LMA versus a VESPA protocol involving endotracheal intubation, recruitment maneuvers, FiO_2 titration, and positive end-expiratory pressure (PEEP) of 8–10 cmH_2O (22). The trial included 76 patients, divided into two groups, and assessed atelectasis using chest CT scans at two time points. Results showed a significantly lower incidence of atelectasis in the VESPA group at Time 2 (28.9%) compared to the control group (84.2%) ($P<0.0001$), with bilateral atelectasis being much less common in the VESPA group (7.9% *vs.* 71.1%) ($P<0.0001$) (22). No significant differences in complications were observed between the groups (22).

Total intravenous anesthesia (TIVA) with propofol and muscle paralysis is also preferred (20). To reduce the risk of atelectasis associated with prolonged intubation, rapid-sequence intubation using 100% oxygen should be avoided. Instead, quick intubation with non-depolarizing muscle relaxants is recommended. Applying PEEP during induction can also help prevent atelectasis (23). While volatile anesthetics can be used, the need to frequently open the circuit for the bronchoscope may complicate anesthesia management.

Intraprocedural considerations

After intubation, adjusting the FiO_2 to the lowest acceptable level can enhance airway visualization. Unless there are specific contraindications (such as acute respiratory distress syndrome or recent surgeries), it is recommended to perform up to four recruitment maneuvers at plateau pressures of 30–40 cmH_2O right after intubation (17). This helps reverse any atelectasis and allows for the assessment of hemodynamic stability, particularly if intubation was prolonged.

In situations where hemodynamic stability is a concern, traditional recruitment techniques may not be practical. It is essential to use PEEP carefully from the pre-induction phase onward, adjusting it based on the patient's hemodynamic response. A PEEP of 10–12 cmH_2O is typically effective for upper lobe biopsies, while even greater PEEP may be required for lower lobe biopsies, especially in obese patients who are at a higher risk of atelectasis. Increasing tidal volumes can also be considered if the patient is able to tolerate them. Using higher levels of PEEP and tidal volumes can enhance lung inflation (24). However, these settings must be tailored to the patient's hemodynamic stability, particularly in obese individuals or those with lung conditions, as they are more susceptible to injuries like barotrauma or volutrauma. The risk of barotrauma can be reduced by minimizing the stress of repeatedly expanding the alveoli and keeping them within a favorable range of lung compliance. Although this approach may seem contrary to traditional methods that advocate for lower tidal volumes to avoid lung injury, achieving optimal conditions for airway visualization and accurate biopsy necessitates these higher settings.

A breath-hold is essential during image-guided bronchoscopy to minimize motion artifacts and ensure clearer images, particularly in techniques like fluoroscopic navigation and cone beam CT (CBCT) (25). The breath-hold should occur at peak inspiration, not at end-expiration, and can be managed either automatically by the anesthesia machine or manually. Manual control involves switching to manual ventilator mode and adjusting the adjustable pressure-limiting (APL) valve to maintain consistent circuit pressure and PEEP while minimizing diaphragmatic movement.

The breath-hold should be sustained long enough for pressures to stabilize throughout the bronchial tree, typically 5–10 seconds before imaging begins. This approach enhances image clarity and accuracy for lesion localization while ensuring optimal bronchial dilation. The breath-hold can be maintained for as long as the patient is able to tolerate it. However, prolonged breath-holding may lead to hemodynamic changes, so careful monitoring is necessary.

The strategies listed above has been described in lung navigation ventilation protocol (LNVP) (26). LNVP is a more aggressive ventilation strategy compared to

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Table 1 Recommendations of LNVP and VESPA

Aspect	LNVP	VESPA
Primary objective	Manages atelectasis and respiratory motion	Primarily addresses atelectasis
Anesthesia type	TIVA	TIVA
Intubation	Endotracheal tube (>8.0 mm)	Endotracheal tube (7.0–8.0 mm)
Post intubation	Recruitment maneuver is performed immediately after intubation (bagging 30 cmH_2O over 30 seconds or 40 cmH_2O over 40 seconds)	Recruitment maneuver is performed immediately after intubation (10 consecutive breaths at a plateau pressure of 40 cmH_2O with a PEEP of 20 cmH_2O in pressure control mode)
Ventilation strategy	Upper/middle lobe targets: PEEP set to 10–15 cmH_2O. Lower lobe targets: PEEP set to 15–20 cmH_2O. Tidal volume 6–8 cc/kg IBW. Apneic breath-hold	PEEP set to 8–10 cmH_2O. Tidal volume 6–8 cc/kg IBW. Apneic breath-hold
Oxygen strategy	Lowest tolerable FiO_2	FiO_2 titration, typically <100%

FiO_2, fraction of inspired oxygen; IBW, ideal body weight; LNVP, lung navigation ventilation protocol; PEEP, positive end-expiratory pressure; TIVA, total intravenous anesthesia; VESPA, ventilatory strategy to prevent atelectasis.

VESPA as the former uses high PEEP, high tidal volume (10–12 cc/kg ideal body weight), and an apneic breath-hold strategy to manage both atelectasis and respiratory motion, while VESPA primarily targets only atelectasis (22,26). *Table 1* provides a summary of the recommendations of VESPA and LNVP.

Post procedural considerations

Standard procedures for reversing anesthesia and evaluating readiness for extubation should be followed, including suctioning any secretions. Post-procedure discharge criteria must be met, and a chest X-ray is advised to rule out complications like pneumothorax. Additionally, patients should be fully reversed from neuromuscular paralysis.

Electromagnetic NB and DT

The first navigational systems were electromagnetic navigation bronchoscopy (ENB). This technology used an electromagnetic field to track a sensor around the patient's body. By mapping this field to a 3D reconstruction of the patient's anatomy from CT images, the sensor's position could be displayed on a virtual 3D lung map. This differs from virtual bronchoscopy, which only uses CT scans to create images of the airways without tracking position of the sensor or probe. The first ENB platformed, superDimension™ (Medtronic, Minneapolis, MN, USA) was released in 2004, with the first human trial using this technology published in 2006 (27). Since its inception, there have been numerous studies evaluating the diagnostic yield of superDimension™, with three meta-analyses showing pooled diagnostic yields of 65–70%, albeit studies had varying definition of diagnostic yield (28-30).

The other electromagnetic navigation (EMN) platform on the market is SPiN Thoracic Navigation System™ by Veran Medical Technologies™ (St. Louis, MO, USA). The SPiN Thoracic Navigation System™ differs significantly from superDimension™ by offering complementary tools called Always-On Tip Tracked® Instruments, which contain electromagnetic sensors. These sensors enable continuous tracking of the instrument's position and the target lesion during the procedure, potentially reducing the need for fluoroscopy.

The NAVIGATE trial was a prospective, multi-center study with over 1,215 participants with suspicious lung nodules, that assessed the effectiveness and safety of ENB for diagnosing peripheral lung lesions. The results showed that 94% of patients successfully had navigation completed and tissue samples taken (31). Over 12 months, the diagnostic yield was 73%. Additionally, the trial reported a low rate of significant ENB-related complications, including pneumothorax (2.9%), hemorrhage (1.5%), and respiratory failure (0.7%) (31). A metanalysis found the pooled complication rates of 2.0% for pneumothorax, 1.0% for minor bronchopulmonary bleeding, 0.8% for major bronchopulmonary bleeding, and 0.6% for acute respiratory failure and pooled sensitivity and specificity for diagnosing malignancy to be 77% and 100% respectively (32).

Medtronic (Minneapolis, MN, USA) has upgraded its electromagnetic navigation platform, superDimension™,

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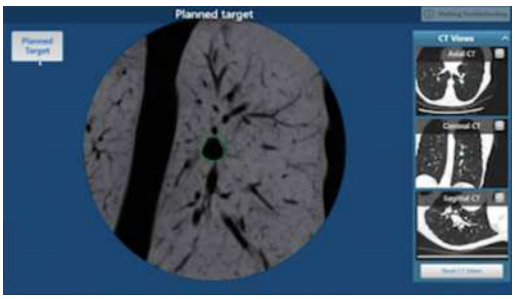


Figure 2 Digital tomosynthesis image of lung nodule using Illumisite. Adapted from Ravikumar N, Ho E, Wagh A, *et al.* Advanced Imaging for Robotic Bronchoscopy: A Review. Diagnostics (Basel) 2023;13:990.

by integrating DT into the Illumisite™ system. This new platform, which replaces the original navigation console, connects to a traditional X-ray fluoroscopy C-arm. Initially, navigation to a target is guided by a preplanned pathway from a prior CT scan. Following this, the C-arm rotates to capture a DT image, either manually or automatically. Once the nodule is identified through software and clinician input, the navigation pathway is updated to reflect the nodule's real-time position as demonstrated in *Figure 2*. However, the platform currently does not support multi-plane or 3D imaging of the target nodule and catheter, and its navigation adjustments are compatible only with the Illumisite™ system. While DT may have limitations in diagnostic imaging, it effectively helps in procedural contexts by clarifying the spatial relationships between small lesions and biopsy tools. The real-time localization of navigation probe allows to overcome the CT-body divergence. In fact, a retrospective study by Aboudara and colleagues revealed a 25% absolute increase in diagnostic yield, achieving 79% compared to 54% with standard navigation alone (33).

LungVision™

LungVision™ by BodyVision® (Ramat Ha Sharon, Israel) is another platform that uses DT. It connects to a conventional X-ray fluoroscopy C-arm to create images and relies on fluoroscopic rather than electromagnetic navigation. After initial bronchoscopic navigation, a C-arm spin captures a tomosynthesis image, also known as C-arm based tomography (CABT). By using the platform's proprietary software, the operator can identify the target in real time using the tomosynthesis image and this adjusts the target's real-time location as can be seen in *Figure 3A*. Unlike Illumisite™, LungVision™ offers augmented fluoroscopy which identifies and labels a lung lesion on a standard 2D fluoroscopy image as well as the pre-planned pathways, allowing for real-time visualization of the relationship between the nodule and biopsy tools as seen in *Figure 3B*. Additionally, the CABT capability allows for visualization of tool-in-lesion. The most recent version of LungVision™ incorporates a feature called AI Tomo. This feature enhances the image quality of the CABT using AI, allowing the operators to track the location of the scope and different tools in real-time to help overcome CTBD. A single-centered prospective study showed a diagnostic yield of 81.8% while, Cicenia and colleagues demonstrated nodule localization rate of 93% and overall diagnostic yield of 75.4% in a multicenter study (34,35). More recently, the combination of LungVision™ with robotic-assisted bronchoscopy (RAB) was shown to have a diagnostic yield of 84% in a retrospective review of 45 patients (36).

RAB

Currently, there are three RAB platforms on the market: Monarch™ platform by Auris Health (Redwood City, CA, USA), Ion™ endoluminal robotic bronchoscopy platform by Intuitive Surgical (Sunnyvale, CA, USA) and The Galaxy System™ by Noah Medical (San Carlos, CA, USA). The Ion system currently is able to engage with Cios® to offer adjunctive advanced imaging that will update lesion location in real time. A recent multicenter retrospective study at two tertiary care centers found a 85.4% diagnostic yield of small peripheral nodules, and no difference in diagnostic yield between groups with and without the use of mobile cone beam (37). Additionally, utilizing the BodyVision platform along with the Monarch Robotic system has also been used successfully to update real-time lung nodule location and improve diagnostic yield (35). However, out of these commercially available systems, The Galaxy System™ is the only one that integrates proprietary DT software. It is an EMN system that utilizes a disposable, single thin bronchoscope with a 4.0-mm outer diameter (OD) that has an integrated camera, light source, and 2.1 mm working channel (WC) (*Figure 4*). The first in human trial of this system included 18 patients, with average nodule size of 20 mm and average distance from the pleura of 11.6 mm, with target being successfully reached in 100% of cases and a diagnostic yield of 89.5% using the strict definition of diagnostic yield (38).

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Figure 3 LungVision system. (A) LungVision™ CABT image demonstrating tool in lesion. (B) Real time augmented fluoroscopy example of tool in lesion using 2D fluoroscopy. 2D, two-dimensional; CABT, C-arm based tomography.



Figure 4 Galaxy system. (A) Initial CT image of a partial ground glass opacity target using Galaxy. (B) Initial tomosynthesis of navigated robotic bronchoscope. (C) Realignment of bronchoscope and tool in lesion view using augmented fluoroscopy. CT, computed tomography.

DT and bronchoscopic tools

The diagnostic yield of bronchoscopic sampling techniques, including transbronchial needle aspiration (TBNA), forceps biopsy (FB), and cryobiopsies varies depending on the nature of the lesion, the method employed, and the experience of the operator. Overall, the combination of these methods enhances the diagnostic capabilities of bronchoscopy. Prior initial studies using TBNA, FB and brushings for peripheral lung nodules with EMN and DT have reported higher diagnostic yields ranging from 79–83% compared to standard EMN (33,39). A study examining the diagnosis of pulmonary nodules with real-time augmented fluoroscopic navigation followed by a sequence of biopsies—TBNA, FB and cryobiopsies—reported a diagnostic yield of 77.8%, with the use of cryoprobe contributing to nine additional diagnoses (34). Another similar study, showed that the addition of cryoprobe to add 22 more diagnoses for peripheral pulmonary nodules, increasing the yield by 8.6% compared to conventional methods like TBNA, FB and brushing (40), while a third study showed the addition of cryoprobe can improve the diagnostic yield from 80% to 93% (41).

DT *vs.* CBCT

The challenge of accurately localizing targets during bronchoscopy has spurred interest in advanced imaging solutions that offer real-time, multi-axis visualization of lesions. CBCT has emerged as a key tool for confirming the location of peripheral lesions. Unlike conventional CT, which uses fan-shaped X-ray beams and multiple detectors over several rotations, CBCT employs a cone-shaped X-ray beam that captures 2D images on a flat detector, enabling

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Table 2 Digital tomosynthesis *vs.* CBCT

Feature	CBCT	Digital tomosynthesis
Imaging technique	Provides 3D imaging by rotating the X-ray source and detector around the patient 180°–200°. Provides about 200–400 images	Uses multiple X-ray images over 50° to create a series of 2D slices that can be reconstructed. Provides about 50 images
Resolution	High-resolution, 3D images. Can view some soft tissue components as well	Provides high-quality 2D slices with lower resolution compared to CBCT. Lung nodules are able to be visualized
Radiation dose	1 mSv	0.5 mSv
Navigational systems	Can be used with Ion	Can be used with Illumisite, LungVision, Galaxy
Cost	$50,000–$150,000	C-arm ranges from $25,000–$85,000

2D, two-dimensional; 3D, three-dimensional; CBCT, cone beam computed tomography.



Figure 5 Cone beam CT augmented fluoroscopy image of robotic bronchoscope tool in lesion. CT, computed tomography.

volumetric data acquisition in a single rotation and shorter time frame (42). CBCT differs from tomosynthesis by using a wider cone-shaped X-ray beam to capture 200–400 images (depending on the protocol) over a 180–200° rotation around the patient (see *Table 2*). This allows for complete image reconstruction without blurred surrounding anatomy. CBCT provides detailed views of multiple planes, including bone, soft tissue, and cartilage, offering improved image quality due to the larger beam, increased angulation, and broader field of view, though at the cost of a higher radiation dose. As with tomosynthesis, additional scans can further increase the radiation dose, depending on the protocol. While CBCT delivers image quality comparable to conventional CT, it typically has a lower contrast ratio (42). Early studies indicate that visualizing a biopsy tool within a lesion significantly enhances diagnostic yield (43). Additionally, many CBCT platforms offer augmented fluoroscopy, overlaying 3D images onto 2D real-time fluoroscopic views for better sampling guidance as can be seen in *Figure 5* (29). Although radiation doses vary widely depending on factors like model and scan duration, CBCT generally exposes patients to less radiation than conventional CT (44). Patient exposure from the primary X-ray is measured as the effective dose (ED) in millisieverts (mSv), which reflects the overall radiation risk to the body. For example, a lung cancer screening CT has an estimated ED of about 1.5 mSv, while a single CBCT lung scan is around 1 mSv. A tomosynthesis sweep typically has an ED of 0.5 mSv, though using higher frame rates and slower sweep speeds could increase its ED beyond that of CBCT (45). Several studies have demonstrated improved diagnostic yields when integrating CBCT with bronchoscopy techniques, with reported yields ranging from 70% to 92% for detecting both malignant and benign lesions (46-49). A CBCT machine is generally more expensive than a C-arm, with a typical CBCT costing between $50,000 and $150,000 for a new unit, while a C-arm can range from $25,000 to $85,000 depending on its size and features (50,51). Currently, there are no head-to-head comparison of NB using CBCT *vs.* DT. However, we eagerly await the results of the Robotic versus Electromagnetic Bronchoscopy for Pulmonary Lesion Assessment (RELIANT) which is the first pragmatic randomized controlled trial comparing the

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diagnostic yield of a robotic assisted platform (shape sensing Ion™) with CBCT to Illumisite™ system (52).

Conclusions

Recent technological advancements in biopsy techniques of peripheral pulmonary lesions including advanced imaging to improve real-time localization and overcome CTBD and atelectasis have contributed to a paradigm shift in the approach to lung biopsy. DT imaging enhances real-time visualization of biopsy tools within lesions, boosting bronchoscopists' confidence, especially for benign findings. However, more studies are needed to assess the impact on diagnostic yield, along with cost-effectiveness studies to evaluate their broader use. Additionally, the consistent use of strict definition of diagnostic yield in studies allows for more accurate comparisons of different technologies (53). Although CBCT offers substantially better imaging, DT 3D reconstruction algorithms are rapidly growing and improving. While DT shows promise, current clinical research is still in its early phases and further multicenter, prospective studies including operators of varying skill are needed.

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Footnote

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