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Navigation Bronchoscopy

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Keywords

Computed tomography-guided · Navigation bronchoscopy · Virtual bronchoscopy

Abstract

With the advent of lung cancer screening, and the increasingly frequent use of computed tomography (CT) scanning for investigating non-pulmonary pathology (for example CT coronary angiogram), the number of pulmonary nodules requiring further investigation has risen significantly. Most of these nodules are found in the lung periphery, which presents challenges to biopsy, and many centers rely on transthoracic needle biopsy performed under image guidance by radiologists. However, the desire to minimize complications is driving the development of increasingly accurate navigation bronchoscopy platforms, something that will be crucial in the new era of bronchoscopic therapeutics for lung cancer. This review describes these platforms, summarizes the current evidence for their use, and takes a look at future developments.

Introduction

Navigation bronchoscopy, put simply, is the use of technology (beyond standard cross-sectional imaging) to help the bronchoscopist accurately navigate the bronchoscope to an area of interest beyond the central airways. Although ultrathin bronchoscopes are available with outer diameters of 3 mm or less, the highly variable and complex branching structure of the airways makes it very difficult to be certain of ones location beyond the first few divisions [1], leading to low diagnostic yields [2–4], the need for further invasive procedures, and increasing costs. This uncertainty, coupled with the desire for safer biopsy of peripheral lung lesions, in particular a reduction in pneumothorax and surgical biopsy, has driven the development of a number of different technology platforms designed to allow access to previously inaccessible lesions with a much higher degree of accuracy, opening up the periphery to new diagnostic and treatment opportunities. This is especially important in an era of increasing detection of incidental pulmonary nodules, lung cancer screening, and a shift from central squamous lung cancers to peripheral adenocarcinomas [5]. In addition, the development of endobronchial lung cancer treatments, including a variety of multifunctional ablation probes and intratumoral anticancer drug injections, will demand highly accurate placement of instruments to ensure safe and effective procedures. This article, whilst not intending to be a comprehensive systematic review of all available techniques, provides an overview of the field of navigation bronchoscopy, including the evidence for currently available navigation platforms and their alternatives, as well as looking ahead to potential future technologies.

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Current Gold Standard: Computed Tomography-Guided Lung Biopsy

Currently, the gold standard for the minimally invasive diagnosis of peripheral lesions is computed tomography (CT)-guided transthoracic needle biopsy (TTNB). Pooled sensitivities and specificities for lung cancer in a recent meta-analysis were high for both core needle biopsy and fine needle aspiration (FNA) [6], with values of 0.95 and 0.99, respectively, in the core biopsy group and 0.90 and 0.99, respectively, in the needle aspiration group, although sensitivity ranged from a poor 0.68 up to 0.97. While these pooled values are high, TTNB is not universally suitable and some patients may be at too high a risk for complications.

As the technique, by its very nature, involves the crossing of pleural surfaces, the biggest drawback with CT-guided TTNB is the risk of pneumothorax. Reported rates range widely from <10% to as high as 45% [7, 8]. The largest study published, involving over 15,000 procedures, reported a 15% pneumothorax rate, with 6.6% of patients (approximately 1 in 15) requiring intercostal tube drainage [9], while a similar study from Japan on almost 10,000 biopsies reported a much higher pneumothorax rate of 35% [10]. The risk of pneumothorax is around 11 times greater if the target lesion is <20 mm in diameter (ref) and increases with an increase in the distance from the pleural surface (ref). In addition to size and location, other factors to consider are age and underlying disease, with the highest risk appearing to be in patients aged 60–69 and those with COPD [9]. These factors are particularly important when one considers the nature of nodules detected via lung cancer screening programs. For example, patients in the National Lung Screening Trial in America had an average age of 62 years, were at risk of having COPD, and 40% of all tumors were ≤2 cm in diameter [11].

A more recent meta-analysis, which interestingly did not include the 2 large studies above as they did not meet the entry criteria, attempted to better characterize the overall risks of TTNB, and split procedures into those where core biopsy was attempted and those where only FNA was attempted [12]. Complications were higher with core biopsy than FNA – pneumothorax 25.3 vs. 18.8%; pneumothorax requiring intervention 5.6 vs. 4.3%; hemorrhage 18 vs. 6.4%; and hemoptysis 4.2 vs. 1.7%. Overall complication rates were 38.8 and 24.0%, respectively, with major complication rates of 5.7 and 4.4%.

Other situations where TTNB is high risk include nodules in close proximity to the heart or large vessels, the presence of significant emphysema, lesions near the diaphragm where movement of the lesion peri-biopsy can be a particular problem, and where it is necessary to cross more than one visceral pleural surface. An accurate method of accessing lesions via the airways therefore has the potential to allow safer access to lesions in a number of clinical situations where TTNB may not be desirable or be deemed unsafe by the multidisciplinary team. In particular, any such technique opens up the middle third of the lung, an area where traditional bronchoscopy performs relatively poorly, and the risks of TTNB are increased.

Virtual Navigation Bronchoscopy

The potential advantages of obtaining adequate diagnostic material without traversing the pleura are self-evident. Traditional bronchoscopic transbronchial lung biopsy performs poorly in the setting of solitary pulmonary lesions, and although the use of fluoroscopic guidance has been shown to significantly improve the diagnostic yield [13, 14], not all lesions are visible at fluoroscopy, and performance is significantly below that of CT-guided TTNB. The yield of standard bronchoscopy varies with distance from the hilum and lesion size [2], with sampling of peripheral lesions of <2 cm in diameter, including those from lung cancer screening programs, having a diagnostic yield as low as 13.5% [3, 4]. The development of software that can generate accurate 3-dimensional reconstructions of the airways led to the concept of virtual bronchoscopy and platforms designed to allow (pseudo-) real-time matching of virtual and actual bronchoscopic images, with the potential for more accurate pathway selection [1].

There are 2 phases to virtual bronchoscopic navigation (VBN). The first of these is the planning phase. Once a target has been identified on CT, software can then construct a virtual bronchial tree and then identify one or more pathways through the airways by which a lesion can be reached. This relies heavily on good-quality thin-slice CT scans, as the ability of any system to render accurate maps of the distal airways is directly linked to the resolution of the scans presented, and a lack of motion artifact. The bronchoscopist can then follow those pathways as far out as the bronchoscope and airway diameters allow. A number of different systems have been or are in development, but all essentially rely on the same basic principles. The virtual bronchial tree is displayed on a monitor next to the real-time camera images, and colored lines used to identify one or more routes to the lesion, and the position of the bronchoscope tip can also be viewed in relation to axial, sagittal, and coronal CT images. Platforms differ in how they align virtual and real images, with both manual matching and automatic pattern recognition being utilized, the latter providing the ability to superimpose those suggested pathways onto the virtual image.

Early studies of VNB, predominantly from the group at Hokkaido University, Japan, demonstrated its utility not only in allowing the bronchoscopist to navigate to the correct airway but also in increasing diagnostic yields. Initial reports included its use for barium marking of pulmonary nodules prior to thoracic surgical resection, with barium marking within 10 mm of the lesion in 27/31 nodules targeted (median 4 mm), with navigation achieved up to ninth generation bronchi (median sixth generation) [15, 16]. Two very similar case series then demonstrated its safety, feasibility, and potential usefulness in combination with both ultrathin bronchoscopy [17] and radial endobronchial ultrasound (rEBUS) via a guide sheath [18]. When using rEBUS, 24/30 lesions (80%) were visualized, with a diagnostic yield of 63%. However, diagnostic sensitivities were 44% for lesions <20 mm and 92% for lesions 20–30 mm in mean diameter. Using the ultrathin bronchoscope in lesions <20 mm, a diagnosis was obtained in 17/26 (65%) lesions, and navigation was possible to a higher generation of airway than with rEBUS alone (5th–8th vs. 3rd–6th). Eighteen lesions were in the upper lobes, often a more challenging location for distal navigation. The lesion was not reachable even with the ultrathin bronchoscope in 3 cases. Complications were not seen with either technique. A follow-up study by the same group in 37 consecutive patients with 38 peripheral lesions up to 30 mm, with the addition of fluoroscopy to confirm forceps position prior to biopsy, reported better yields, with navigation down the planned route in 36/38 lesions (95%), advancement of the biopsy forceps to 33/38 lesions (87%), and a diagnosis in 31 lesions (82%) [19]. A similar study from a different Japanese group produced comparable results [20]. Thirty-seven patients were enrolled, with a diagnosis established in 28 patients (diagnostic yield 76%), although unlike with rEBUS, lesion size did not appear to alter yield (≤20 mm 76.9%, 21–30 mm 76.5%, ≥31 mm 71.4%) in this study. In one study of 69 patients specifically looking at examination time, VNB also reduced the time to first biopsy and total examination time when compared to historical controls ($p < 0.05$) [21].

This early work led to the Virtual Navigation in Japan Trial [22], a prospective multicenter study specifically assessing the value of VBN in combination with rEBUS in the diagnosis of peripheral lesions up to 30 mm in diameter. One hundred and ninety-nine patients were randomized to a procedure with or without VBN. Sites of specimen sampling were verified using EBUS with a guide sheath, and fluoroscopy was used to verify biopsy forceps position. The diagnostic yield was 80% for procedures using VNB and 67% for procedures without (p = 0.032). There was also a reduction in procedure time (24 vs. 26 min, p = 0.016) and in time to first biopsy (8 vs. 10 min, p = 0.045). The investigators reported only 1 adverse event, a pneumothorax in the non-VNB group.

LungPoint is a platform that has been available for a number of years and makes up the VNB component of the Archimedes system for transparenchymal nodule access, discussed below. Single-center noncontrolled evidence similar to that discussed in the previous paragraph exists for this platform, with successful navigation along the planned route using a thin bronchoscope in 25/25 patients and a diagnostic yield of 80%. One patient (4%) developed a pneumothorax that did not require additional intervention [23]. A larger study that included the use of rEBUS in 68 patients with lesions <30 mm reported a similar yield at 78%, but the most significant contributor to a successful diagnosis was the location of the lesion with respect to the airway (within vs. adjacent to the lesion = 92.1 vs. 60.0%, respectively) [24]. In a subanalysis of the Virtual Navigation in Japan Trial [22], Asano et al. [25] also found that the yield was significantly higher in those cases where there was involvement of an airway versus those without, with diagnostic yields of 94.4 and 77.8%, respectively (p = 0.004). The difference was particularly striking when the lesion was <20 mm in diameter – 94.6 vs. 70.7%, p = 0.006.

However, 3 recent papers have challenged the utility of VNB in certain situations and perhaps contradicted some of the earlier evidence. The first, a single-center study of 115 patients randomized assigned to rEBUS with or without VNB, found no difference between the overall diagnostic yield (p = 0.419) in the 2 arms of the trial, although there was a difference for small nodules <20 mm (p = 0.041) [26]. The addition of VNB did not shorten the procedure time or reduce the incidence of complications. Similar findings were reported in a much larger, multicenter study which compared the diagnostic yield using 3 approaches [27]. Subjects were randomized to a standard bronchoscopy, a rEBUS-guided bronchoscopy, or a bronchoscopy combining both rEBUS and VBN. While both guided bronchoscopy groups were superior to standard bronchoscopy, there was again no difference in diagnos-

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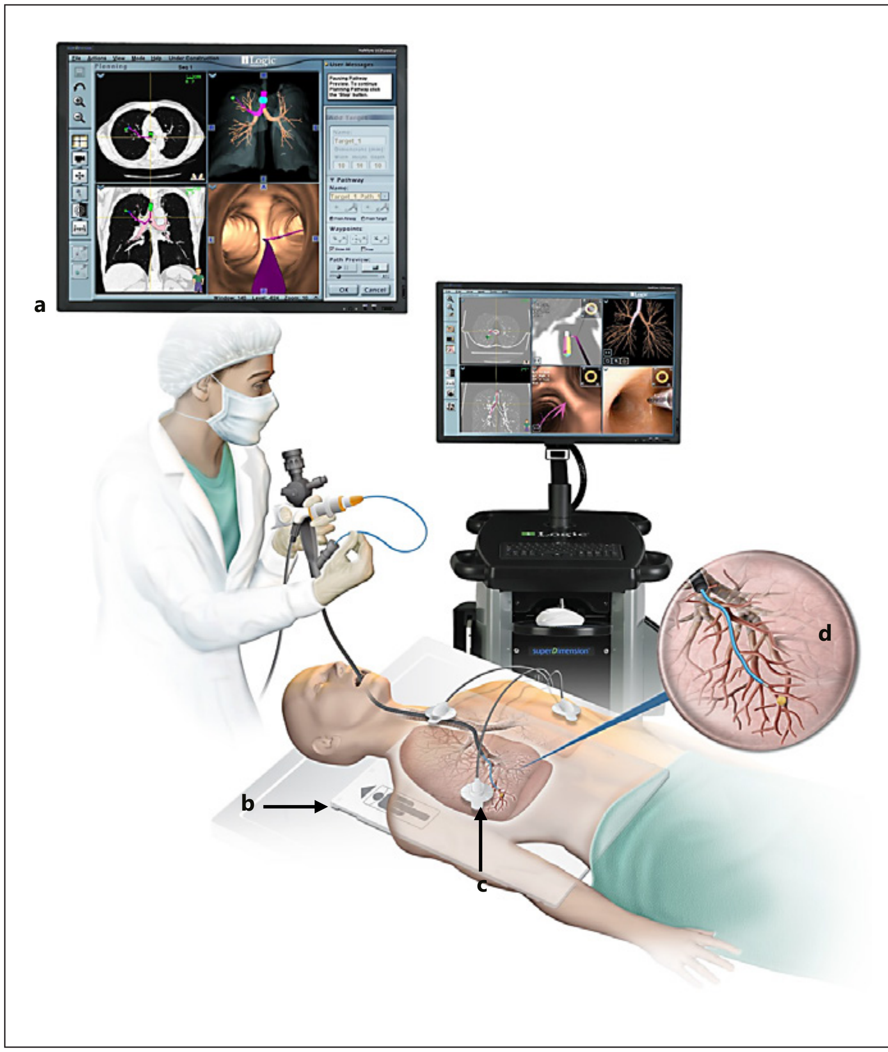

Fig. 1. The superDimension navigation platform. **a** Planning screen. **b** Location board creates electromagnetic field. **c** Patient sensors to track locatable guide position and account for patient movement. **d** Locatable guide with 360°.

tic yield or total procedure time between the groups with and without VNB. The GUIBRO group studied the addition of VNB to ultrathin bronchoscopy in a multicenter study [28]. Fifty-five VNB cases were collected prospectively and compared to 110 historical controls. No statistical difference was found between the 2 groups in diagnostic yield, although this was relatively low in both groups at 47 and 40%, respectively, even in lesions <20 mm. However, in a subgroup of cases where the lesion was endobronchial in nature and the VNB segmentation was optimal, there was a large difference in yield versus those where either condition was not met (85 vs. 30% when segmentation was suboptimal vs. 20% when segmentation was optimal but the lesion was extraluminal).

Virtual navigation bronchoscopy does appear to improve certain aspects of peripheral bronchoscopy and certainly has a better reported safety profile, in particular pneumothorax rate, than TTNA (although no trials prospectively comparing the 2 have been performed). However, its use should be considered carefully when other techniques are available to improve yield, and the bronchoscopist should pay great attention to the planning phases of the procedure to optimize yield.

Electromagnetic Navigation Bronchoscopy

Virtual navigation bronchoscopy relies on the use of a thin bronchoscope to allow direct visualization of and navigation through the distal airways. One different approach to the problem of peripheral lesion sampling is electromagnetic navigation bronchoscopy (ENB). This

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Table 1. Biopsy outcomes from the NAVIGATE study [31]

	Excluding deferred cases (n = 1,053), % (n)	Low estimate (n = 1,157), % (n)	High estimate (n = 1,157), % (n)
12-month diagnostic yield ([TP+TN]/all attempted biopsies)	72.9 (768/1,053)	66.4 (768/1,157)	75.4 (872/1,157)
Sensitivity for malignancy (TP/[TP+FN])	68.8 (484/704)	59.9 (484/808)	68.8 (484/704)
Specificity for malignancy (TN/[FP+TN])	100 (284/284)	100 (284/284)	100 (388/388)
Positive predictive value (TP/[TP+FP])	100 (484/484)	100 (484/484)	100 (484/484)
Negative predictive value (TN/[FN+TN])	56.3 (284/504)	46.7 (284/608)	63.8 (388/608)

technique involves the generation of an electromagnetic field around the patient, with the virtual bronchoscopy aligned to the patients' airways within that electromagnetic field by the selection of a number of predetermined central landmarks. A steerable catheter with a sensor tip to locate the position of the catheter within 3D space is then used to navigate biopsy tools to the lesion without the need for visualization of the pathway. Figure 1 illustrates the process (superDimension Navigation System, Medtronic, Minneapolis, MN, USA).

Since the first study in human subjects [29], an open-label, prospective study with positive biopsy diagnoses in 9/13 cases (69%) of peripheral lesions beyond the reach of conventional bronchoscopy, there have been many retrospective and several prospective studies assessing the diagnostic utility of ENB. One randomized controlled trial has been published, involving 3 separate study arms [30]. Patients were randomized to either rEBUS, ENB, or a combination of the 2. Surgical lung biopsy was used in the event of a nondiagnostic sample. A definitive histological diagnosis was established in 118/120 with diagnostic yields of 88% for the combined procedure, 69% for EBUS alone, and 59% for ENB alone ($p = 0.02$). There was no significant differences in pneumothorax rates between the groups (5–8%).

The NAVIGATE study [31] provides the largest pool of patients, in a multicenter (but not controlled) setting, using a variety of techniques, with differing experience, and variations in local referral indications and pathways – effectively mimicking real life. Twenty-nine centers in the United States recruited 1,215 patients, 1,157 of whom underwent biopsy (total of 1,344 lesions). Two-thirds of lesions were in the peripheral third of the lung with a median distance from the pleura of 9.0 mm, and 49% were <20 mm in diameter. Concurrent imaging included fluoroscopy in 91%, rEBUS in 57%, and cone-beam CT in 5%. Follow-up was completed in 98.9% (1,202/1,215) at 1 month and 80.3% (976/1,215) at 12 months. Follow-up regarding the initial ENB-aided diagnosis was obtained in 91.0% of biopsy subjects. Among the 1,157 biopsy cases, navigation was successful and tissue was obtained in a remarkable 94.4% (1,092/1,157). The diagnostic yield was 72.9% when assessed at 1 year (taken as true positives and true negatives, not including deferred cases). Sensitivity for malignancy and NPV were 68.8 and 56.3%, respectively. Further details are shown in Table 1.

The appearance on CT of a bronchus sign is an important factor in determining the success of the procedure, with one single-center study in 51 subjects showing a large difference in diagnostic yield between those cases with (79%) and without (31%) a bronchus sign on pre-procedure imaging [32]. This remained the only significant factor in obtaining diagnostic material on multivariate analysis (OR 7.6; 95% CI 1.8–31.7). This finding was also seen in a larger single-center cohort from Italy (n = 113), where again a bronchus sign was the only factor that influenced the ability of the operators to obtain diagnostic tissue [33], although this does not appear to be universal across individual studies [34]. None of these 3 studies found lesion size to be a factor in diagnostic yield, and indeed this is a widespread finding in published studies, including where ENB is combined with radial EBUS [30, 35]. The NAVIGATE study has now confirmed these results in a much wider setting, with size, location, use of ROSE, or use of radial EBUS not appearing to alter diagnostic yield (although lesion size <20 mm was a predictor of greater diagnostic yield in univariate, but not multivariate, analysis) [31]. Factors that do appear to affect yield included presence of a bronchus sign ($p < 0.001$), biopsy of multiple lesions ($p = 0.004$), sampling of lymph nodes during the procedure ($p = 0.009$), and the use of multiple sampling tools ($p = 0.04$). Samples obtained have been shown to be suitable for molecular characterization of lung cancer subtypes [36] and kinomic profiling [37].

As well as tissue biopsy, there is an emerging role for ENB in the placement of fiducial markers as well as dye marking of the lung and pleura to assist with surgery and radiotherapy. Indeed, in the NAVIGATE study, ENB was used for fiducial marker placement in 258/1,215 (21.2%) patients (Bowling et al. [38]). A mean of 2.2 markers were placed per patient, with >99% being deemed to be correctly placed (albeit on subjective assessment by the operator), an extraordinarily high rate especially given that almost one-third (31.8%) of the procedures were not performed under general anesthesia. Fiducial markers placed using ENB also appear to remain in place on follow-up imaging in a majority of cases (94% in NAVIGATE [31], 90% in an earlier single-center study [39]). Localization of nodules during surgery using dye marking via ENB is particularly useful for impalpable and subsolid nodules, potentially allowing for a more target resection. Several studies have demonstrated the feasibility and safety of this approach, with successful nodule localization rates of 91–100% [40–46]. Other approaches that have reported success include retaining the locatable guide during surgery to cause protuberance of the visceral pleura [47], and the injection of a fibrin sealant mixed with dye to improve both visual and tactile localization of the lesion [48].

Electromagnetic bronchoscopy has a good safety profile, with studies reporting low and acceptable incidences of bleeding and pneumothorax. In the 1,215 patients in the NAVIGATE study [31], there were 52 pneumothoraces (4.3%), with 35 requiring intervention or hospitalization (2.9%), considerably lower than rates reported with CT-guided TTNA. Bleeding occurred in 30 (2.5%) patients, and there was only 1 peri-procedure death recorded, related to anesthesia, and the authors report no deaths related to the ENB device or associated tools. Given the nature of the study, these results are likely to be representative of "real-world" outcomes. In particular, ENB may be better suited for use in those with COPD/emphysema or those with poor lung function where the risk of pneumothorax from TTNB is elevated or the patient's ability to tolerate a pneumothorax is reduced. Indeed, in the NAVIGATE study, COPD was not a significant multivariate predictor of complications, and the severity of lung function impairment (FEV_1, TLCO) was not associated with increased complications [49]. The use of an electromagnetic field has led to some concern over the use of ENB in those with implantable cardiac devices, but safety has been demonstrated for pacemakers and implantable cardiac defibrillators (ICDs) [50], and Magnani et al. [51] tested that ICDs operated correctly in 13 patients undergoing an ICD implantation or elective replacement. All rescued the patients from induced ventricular fibrillation during ENB.

There are, however, some inherent disadvantages of both virtual bronchoscopy and ENB over CT-guided TTNB. By the very nature of the procedure, CT-guided TTNB allows same-day cross-sectional imaging to be obtained, allowing for the assessment of any change in lesion size or characteristics at the time of the proposed biopsy. This can avoid the risks associated with unnecessary procedures in patients with benign lesions. One study in 116 patients identified a small but significant cohort of patients attending for ENB procedures in whom same-day repeat CT imaging demonstrated a reduction in the size of the lesion and who therefore no longer required the procedure [52]. Another potential problem arises when considering the difference between lesion position at full inspiration (the phase of respiration in which most CT scans are performed) and that during tidal breathing, leading to small but potentially important registration errors. Chen et al. [53] studied 85 lesions in 46 patients and found the average motion of all pulmonary lesions to be 17.6 mm, with lesions located in the lower lobes moving significantly more than those in the upper lobes. Size and distance from the pleura did not significantly impact movement.

ENB has taken VNB one step further but has struggled to integrate into the management algorithms of lung nodule patients in a number of healthcare systems, in spite of evidence that the technique can be learnt very quickly by experienced bronchoscopists [54]. There are concerns around the cost of the procedure, availability of theatre space, and diagnostic yield when compared to TTNA, particularly in hospitals with rapid access to quality interventional radiology services. The problem of targeting extra-luminal lesions still exists, although new tools have been developed to allow biopsy through the distal airway wall, and dedicated aspiration needles are available. Nonetheless, where available in a timely fashion, ENB is an effective and very safe approach to accessing the periphery of the lung and may be best suited to those patients who are at high risk of complications from CT-guided TTNA or to assist with the identification of pulmonary lesions prior to surgery.

Bronchoscopic Transparenchymal Nodule Access

Fused fluoroscopy, already widely used in cardiology and interventional radiology, is an imaging technique that allows the overlay of a pre-procedure CT scan on to real-time 2-dimensional fluoroscopy images obtained during the procedure. Images are then aligned using prespecified landmarks. This fused imaging method has been combined with ENB, with a diagnostic yield ap-

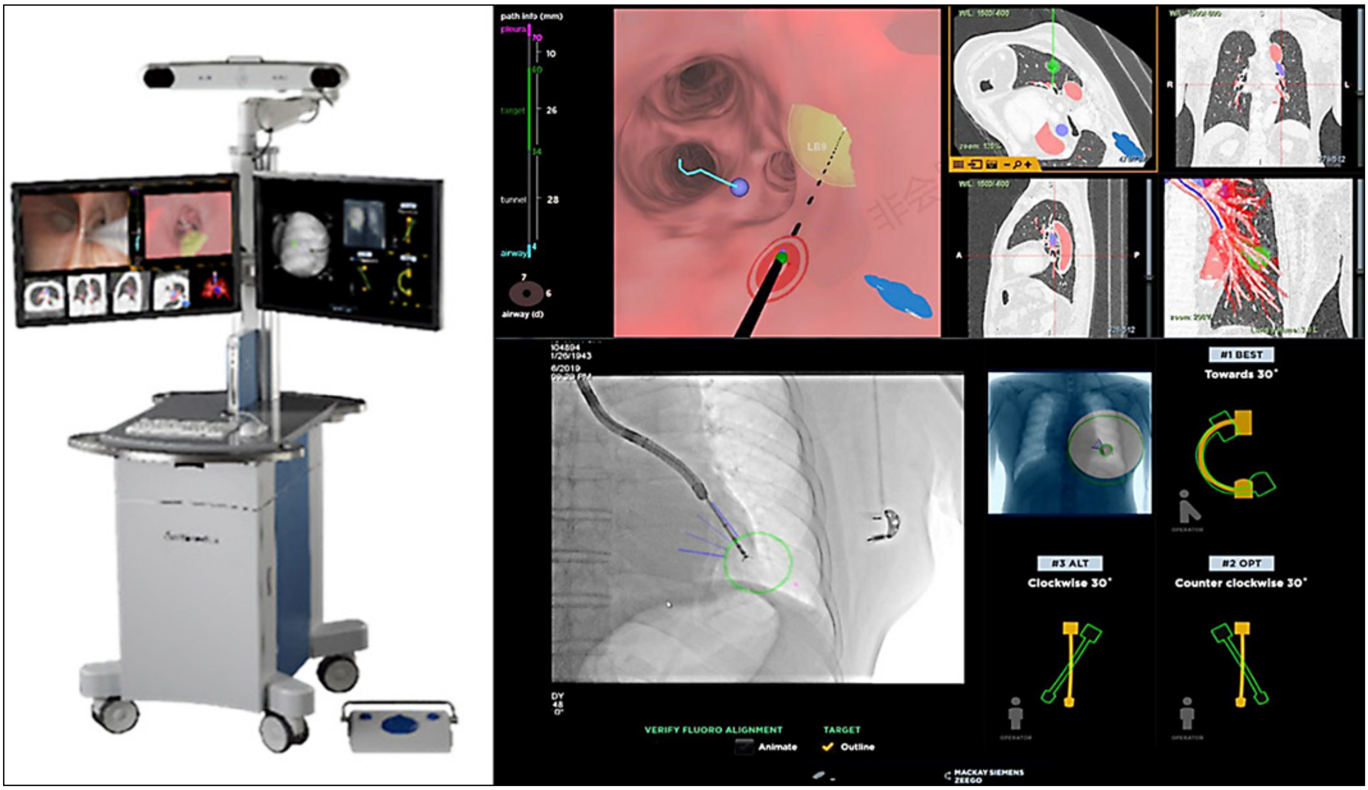

Fig. 2. The Archimedes platform for transparenchymal nodule access. Archimedes display showing tunneling entry point and virtual Doppler, 3D CT reconstructions, and fused fluoroscopy with tunneled forceps at biopsy site.

proaching 85% [55], but is integral to a more recently developed technology that combines fused fluoroscopy with a navigation bronchoscopy platform to allow direct tunneling through the lung to a lesion (Archimedes, Broncus Medical Inc., CA, USA). The procedure is an adaptation and extension of the airway bypass procedure originally developed for the treatment of emphysema [56]. A CT scan is first reconstructed into a 3-dimensional model using the Archimedes Virtual Bronchoscopy Navigation System. The target lesion is then marked, and the software identifies a suitable point of entry in the wall of a proximal bronchus from where a direct avascular tunneling path can be created, as well as generating a virtual bronchoscopy to facilitate precise navigation to that point of entry. The virtual bronchoscopic images identify the entry point in color on the airway wall and also allow visualization of any adjacent vessels. A puncture needle and dedicated dilator balloon are used to create an opening in the bronchial wall, and a sheath containing a blunt stylet is passed through the opening. Fused fluoroscopy is then used to guide this dedicated tunneling tool through the lung parenchyma directly to the lesion (Fig. 2).

Although limited trial evidence is available for this technique (none of it controlled), a first in human study in 12 patients awaiting surgical resection of a solitary pulmonary nodule did not result in any complications, and a tunnel tract to the lesion was established in 10 of the patients. Histology correlated with that obtained at resection, and subsequent histological analysis postresection did not flag an additional safety concern [57]. Harzheim et al. [58] subsequently performed the procedure outside of the operating theater in 6 patients, with a pathway created in 5 of those. The procedures themselves were uneventful, although 2 pneumothoraces were recorded on postprocedure chest radiographs. Once again, adequate biopsies were obtained from all 5 patients in whom a tunnel path was created. Results from a larger cohort of 25 patients with 27 lesions, presented as an abstract [59], demonstrated a diagnostic yield of 85% and no pneumothoraces in spite of the fact that 55% of lesions were within 1 cm of the pleura. The results of a larger prospective multicenter study to confirm the performance of the system in patients with lesions highly suspicious for lung cancer are awaited (ClinicalTrials.gov identifier NCT02867371).

Future Direction

While navigation bronchoscopy, in its current form, has improved the diagnostic ability of bronchoscopy and has a lower rate of serious complications than CT-guided TTNA, there are still concerns in particular about the low negative predictive value [60], problems with registration, and cost. Direct tunneling as seen with BTPNA has the potential to mitigate some of the difficulties with the accuracy of tool manipulation in the extreme periphery of the lung, but more research is needed before this can enter routine clinical practice. With a drive to increasingly minimally invasive procedures across all specialities in medicine and surgery, the true place for these technologies is likely to lie in therapeutics (as opposed to their current role in diagnostics). The ability to precisely place ablation probes, accurately locate tumors for intratumoral injection, or apply local destructive therapies (e.g., thermal vapor) [61] has the potential to transform the speciality of interventional pulmonology, especially in an era of widespread lung cancer screening programs. The ongoing NAVABLATE trial assessing the use of the superDimension platform to guide bronchoscopic microwave ablation lung tumors is currently recruiting (ClinicalTrials.gov identifier NCT03569111).

It is therefore almost inevitable that any future for complex bronchoscopy will involve robotics, and several groups are developing platforms for use in human subjects [62, 63]. Robotic surgery has already improved outcomes and safety in some areas of traditional surgery, particularly in urology and neurosurgery, and the ability for highly accurate movements and minute adjustments of the bronchoscope and associated tools is very appealing. Navigating the nonuniform branching structure of the lung introduces additional complexities, but the precision that robotics can provide is a truly exciting prospect for the interventional bronchoscopist.

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