Review Article

Robotic-assisted bronchoscopy: a narrative review of systems

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Background and Objective: Robotic-assisted bronchoscopy (RAB) has emerged as an advanced technology for lung cancer diagnosis. This review explores the three approved robotic bronchoscopy systems: Ion™ Endoluminal (Intuitive Surgical, Sunnyvale, CA, USA), Monarch™ (Johnson & Johnson, Redwood City, CA, USA), and Galaxy System™ (Noah Medical, San Carlos, CA, USA), and their different operational systems. This narrative review aims to summarize their findings and outcomes for sampling peripheral pulmonary lesions (PPL) suspected of lung cancer.

Methods: A search in PubMed and Google Scholar databases was conducted for articles and abstracts published between January 2018 to May 2024 using the terms "robotic bronchoscopy" or "robotic-assisted bronchoscopy" for biopsy of PPL.

Key Content and Findings: Lung cancer is the leading cause of cancer-related mortality. The introduction of RAB aims to improve the feasibility and safety of sampling PPL. Current literature describes high diagnostic yields with low risk of complications, allowing concurrent hilar and mediastinal staging within the same procedure. RAB can potentially improve early diagnosis and treatment of pulmonary malignancies and survival rate in long term, while progressing towards therapeutic applications in the near future.

Conclusions: As RAB evolves, its potential as a "one-stop shop" for diagnosis, staging, and treatment can positively impact lung cancer detection, focusing on improved patient-centered outcomes and reducing multiple diagnostic and therapeutic procedures.

Keywords: Robotic-assisted bronchoscopy (RAB); shape-sensing technology; electromagnetic navigation (EMN); lung cancer

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Introduction

Lung cancer stands as the leading cause of cancer-related deaths in the United States, surpassing breast, prostate, and colon cancers in mortality rates (1). The severe impact of this malignancy demands a constant search for effective diagnostic and treatment approaches, for which timely screening and detection are crucial to reduce mortality.

New guidelines from the American Cancer Society now recommend annual lung cancer screening for healthy individuals aged 50 to 80 years with a ≥20 pack-year smoking history, regardless of the time since quitting. This expanded eligibility includes an additional 5 million people, potentially preventing more lung cancer deaths (2). Screening has played a vital role, reducing mortality by 16–24% through the detection of asymptomatic malignancies amenable to curative treatment in high-risk individuals (3,4). However, uptake remains low, with approximately only 6% adherence to screening guideline criteria among the eligible population in 2020 (5).

In diagnostic efforts, robotic-assisted bronchoscopy (RAB) has emerged as an advanced technology for early lung cancer detection. Aside from cost-related barriers, including platform expenses and tools, RAB is showing promise in improving diagnostic yield for pulmonary peripheral lesions (PPL). Recent studies highlight RAB's maneuverability, farther reach, and navigational and diagnostic capabilities compared to conventional methods. When available, it is becoming the diagnostic modality of choice. This narrative review aims to summarize the findings and outcomes of the three available robotic platforms, including their different operational systems and characteristics. We present this article in accordance with the Narrative Review reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-456/rc).

Methods

For this narrative review, we conducted a search in the PubMed and Google Scholar databases for articles and abstracts published between January 2018 to May 2024 using the terms "robotic bronchoscopy" or "robotic-assisted bronchoscopy" for biopsy of PPL. The search strategy is detailed in *Table 1*.

Review of systems

Ion™ Robotic Endoluminal System

The Ion™ Robotic Endoluminal System, developed by Intuitive Surgical (Sunnyvale, CA, USA), received approval from the US Food and Drug Administration in February 2019. This system comprises a flexible robotic catheter equipped with shape-sensing fibers along its entire length, a removable video scope for direct visualization during navigation, a planning station, a robot cart with display screens, and a controller featuring a trackball and a scroll wheel (*Figure 1*). The articulating catheter has a 3.5-mm outer diameter (OD) and a 2.0-mm inner diameter (ID) working channel. For direct visualization, a 1.7-mm OD vision probe is inserted via the working channel, although the Ion™ video scope must be removed for biopsying after navigation, precluding live imaging during sampling.

Pre-procedure planning for Ion™ involves a contiguous

Table 1 The search strategy summary

Items	Specification
Date of search	10/01/2023 to 1/5/2024
Databases and other sources searched	PubMed and Google Scholar
Search terms used	"Robotic bronchoscopy" or "robotic-assisted bronchoscopy"
Timeframe	January 2018 to May 2024
Inclusion and exclusion criteria	Inclusion criteria: original articles including retrospective and prospective studies, meta-analysis, and conference abstracts) for human and animal studies, in the English language
	Exclusion criteria: not in the English language
Selection process	The selection process was conducted by A.K. and N.C.C. independently, and later approved by two board-certified interventional pulmonologists. Duplicate results were eliminated. Consideration for additional studies and review of the final references were performed by all authors

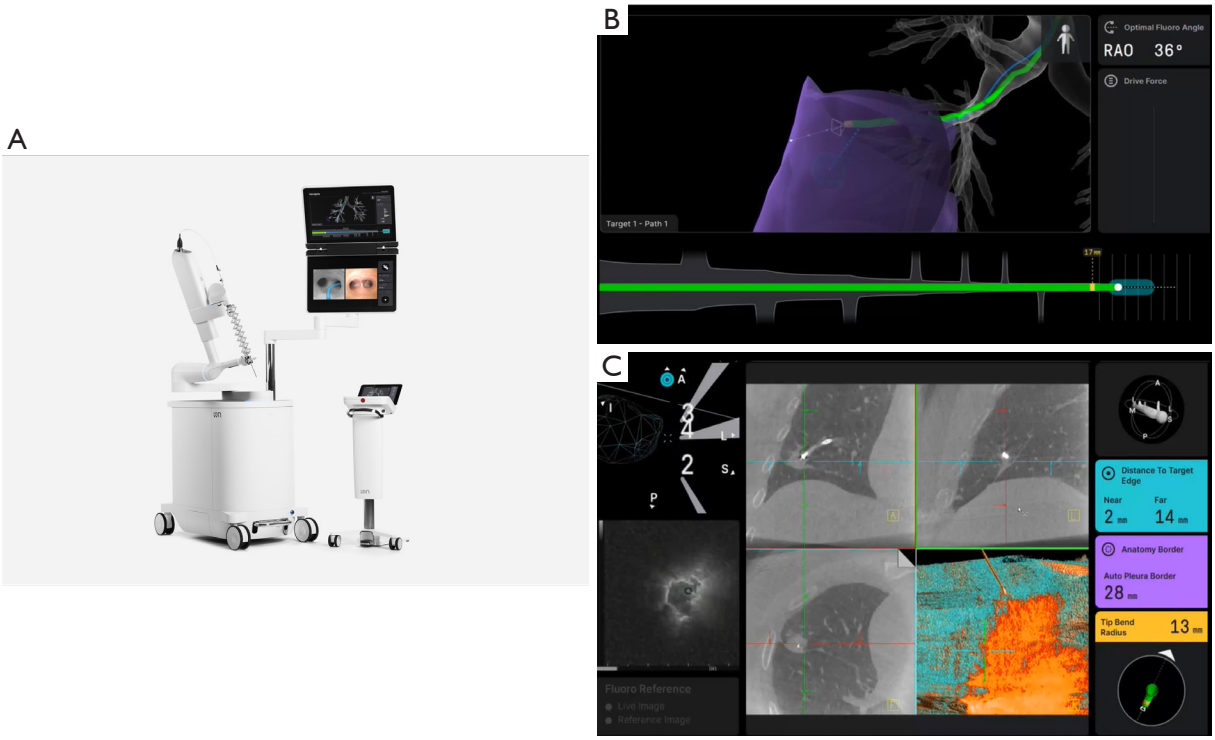

Figure 1 Ion™ Robotic Endoluminal System bronchoscopy. (A) Robotic arm, platform, and screen and trackball controllers (courtesy of Intuitive Surgical). (B) Trackball controllers and navigation screen. (C) Navigation display with 3-dimensional airway pathway in the upper screen, and mobile cone-beam computed tomography images in the axial, coronal, and sagittal view showing biopsy tool-in-lesion in the lower screen.

thin-cut (1.5 mm or less) chest computed tomography (CT) scan. The Ion™ PlanPoint™ software generates a three-dimensional (3D) virtual airway reconstruction, automatically identifying potential pathways towards the target, which can also be done manually if necessary. Once the robotic arm is docked and the catheter introduced, registration begins by aligning the distance and rotation of the main carina between the virtual and live bronchoscopic images. The bronchoscope is then driven into each of the main bronchi, and into the individual lobar and distal airway segments.

The Ion™ platform employs proprietary shape-sensing technology with a fiber embedded along the robotic catheter, providing real-time shape and location feedback. This data enables the catheter tip to correlate with the CT-derived airway map, determining the catheter tip position within the lung. Real-time information on the direction, distance to the target, and distance from the nearest pleura is constantly provided by the system to achieve successful navigation. Fluoroscopy, radial endobronchial ultrasound (rEBUS), and cone-beam CT (CBCT), mobile CBCT (mCBCT) or O-arm CT are used as supportive devices for secondary confirmation of target reach and tool-in-lesion. The catheter is then locked in position, and the vision probe removed to facilitate the use of biopsy tools. A comprehensive comparative description of shape-sensing robotic-assisted bronchoscopy (ssRAB) to the other RAB systems is presented in *Table 2*.

Evidence

In the initial feasibility human study of the Ion™ Endoluminal System, conducted by Fielding *et al.*, 29 consecutive cases were analyzed in a single center (6). The mean lesion size was 12 mm (range, 10–30 mm), with 58.6% of lesions exhibiting a positive bronchus sign. Successful navigation, assisted by rEBUS, was achieved in 96.6% (28/29) of cases. Diagnostic yield was 79.3%, with a follow-up period of 6 months. Subsequently, in the first real-world prospective study, 59 nodules from 52 patients were biopsied, using fine needle aspiration and forceps, and

Table 2 Comparison of the three robotic bronchoscopic platforms

	Monarch™ Robotic Endoscopy System	The Ion™ Robotic Endoluminal System	Galaxy System™
FDA approval	March 2018	February 2019	March 2023
Bronchoscope	4.2 mm inner bronchoscope, 6 mm outer sheath	3.5 mm outer diameter fully articulating catheter with a thin 1.8 mm removable visual probe	4.0 mm outer diameter
Working channel	2.1 mm	2 mm	2.1 mm
Navigation	Electromagnetic navigation along with peripheral vision and real time input from the micro-camera at the tip of the bronchoscope	Fiberoptic shape-sensing and peripheral vision	Electromagnetic navigation with digital tomosynthesis Tool-in-Lesion+ Technology™
Scope reprocessing	Yes	Yes	No (single use disposable scope)
Vision during biopsy	Yes	No	Yes

FDA, United States Food and Drug Administration.

standard CBCT for secondary confirmation of successful navigation (7). The mean nodule size was <20 mm, achieving a 100% target reach rate, 83% overall diagnostic yield and 84% sensitivity for malignancy. Reported complications were two pneumothoraxes, one requiring chest tube insertion.

At Memorial Sloan Kettering Cancer Center, a retrospective single-center trial was conducted, using ssRAB with mCBCT and rEBUS. Encompassing 130 patients with 159 lesions with a median lesion size of 18 mm [interquartile range (IQR), 13–27 mm], successful navigation was achieved in 98.7% (157/159) of cases, resulting in an overall diagnostic yield of 81.7% (8). This yield was stratified by rEBUS view, 93% for concentric and 78.8% for eccentric views. The reported complication rate was 3% (4/130), including 2 patients developing post-procedural pneumothorax requiring tube thoracostomy. Finally, in a large single-center study, Styrvoky *et al.*, performed 200 ssRAB, combined with CBCT and rEBUS, to sample 209 nodules with a mean size of 22.6 mm (±13.3) (9). Diagnostic yield was 91.4% and sensitivity for malignancy was 87.3%. Procedure-related complications were two pneumothoraxes, only one resulting in chest tube insertion.

For PPL under 2 cm, suboptimal diagnostic yields at 66% for <1 cm and 70.4% for 1–2 cm have been reported (8). A retrospective multicenter study led by Abia-Trujillo *et al.* assessed the diagnostic accuracy for small PPL under 2 cm using ssRAB integrated with mCBCT (10). The study included 192 nodules from 173 patients, with 117 nodules utilizing mCBCT and standard C-arm for the remaining ones. Diagnostic yield was 83.8% and 88% for subgroups with and without mCBCT, respectively, highlighting the improved diagnostic performance of ssRAB for small lung nodules regardless of the type of intraprocedural imaging. Likewise, the capability of ssRAB to accurately biopsy ground glass nodules (GGNs) and subsolid nodules (SSNs) with a solid component less than 6 mm, in combination with mCBCT and rEBUS, was evaluated in a cohort study comprising 12 SSNs and 11 pure GGNs (11). ssRAB demonstrated an overall diagnostic yield of 87%, with a sensitivity for malignancy reaching 88.9%. Importantly, no procedure-related complications were observed. Lastly, the same authors recently presented their findings utilizing ssRAB with mCBCT and rEBUS to biopsy multiple nodules within the same procedure, including unilateral and bilateral lesions (12). A total of 46 nodules less than 20 mm in median size were sampled from 22 patients, achieving a diagnostic yield of 84.8% with two complications comprising one grade 2 bleeding in the Nashville Scale and one pneumothorax requiring chest tube. A comprehensive summary of findings for Ion™ Endoluminal is described in *Table 3*.

Monarch™ Robotic Endoscopy System

The Monarch™ Robotic Endoscopy System, developed by Auris Robotics (now Johnson & Johnson) in Redwood City, CA, USA, was the first RAB platform to be approved by the US Food and Drug Administration in March 2018. Comprising a bronchoscope system, cart, and tower, the Monarch™ system employs an articulating bronchoscope within an articulating sheath, each controlled by independent

Table 3 Review of human studies using robotic bronchoscopy platforms

Author, year	Type of study	Patients (n)	Mean/median diameter (mm)	SD/IQR or range	Nodules sampled (n)	Diagnostic yield (%)
Ion™ Robotic Endoluminal System						
Fernandez-Bussy 2024, (12)	Retrospective	22	14	IQR, 1–2	46	86.9
Fernandez-Bussy 2024, (13)	Retrospective	27	16.6	IQR, 13.6–19.9	28	85.7
Abia-Trujillo 2024, (10)	Retrospective	173	12	IQR, 10–14	192	77.4
Abia-Trujillo 2023, (11)	Retrospective	22	18	IQR, 14–20	23	88.9
Gupta 2023, (14)	Abstract prospective	240	16	IQR, 1.1–25	265	76
Hammad Altaq 2023, (15)	Retrospective	42	12	IQR, 10–18	42	88.1
Low 2023, (16)	Retrospective	133	19	IQR, 14–28	143	77
Chambers 2023, (17)	Retrospective	75	20	IQR, 13–35	79	77.2
Styrvoky 2022, (9)	Retrospective	198	22.6	SD: 13.3	209	91.4
Oberg 2022, (18)	Retrospective	112	22	IQR, 13–34.3	120	90
Yu Lee-Mateus 2023, (19)	Retrospective	113	18	IQR, 13–27	113	87.6
Reisenauer 2022, (20)	Prospective	30	17.5	SD: 6.8	30	93.3
Tavakoli 2022, (21)	Abstract retrospective	65	21.2	SD: NA	65	86.2
Kalchiem-Dekel 2022, (8)	Prospective	130	18	IQR, 13–27	159	81.7
Ost 2021(22)	Abstract prospective	155	17	SD: 5.5	155	83
Benn 2021, (7)	Prospective	52	19.6	SD: 10.9	59	83
Ross 2021, (23)	Abstract prospective	45	14	Range, 5–44	58	89
Bawek 2021, (24)	Abstract retrospective	76	17	Range, 6–70	76	92
Ghosh 2021, (25)	Abstract retrospective	95	19	Range, 7–69	103	79.6
Pritchett 2021, (26)	Abstract retrospective	192	15	IQR, 10–21	230	92.2
Folch 2020, (27)	Abstract prospective	129	18.4	SD: 5.44	129	80.6
Fielding 2019, (6)	Prospective	29	12.2	SD: 4.2	29	79.3
Monarch™ Robotic Endoscopy System						
Agrawal 2023, (28)	Retrospective	124	24	IQR, 13–30	124	77
Khan 2023, (29)	Retrospective	264	19.3	Range, 32–72.5	264	85.2
Manley 2023, (30)	Prospective	20	14.5	Range, 8–28	20	80
Hedstrom 2022, (31)	Abstract retrospective	45	16.9	Range, 4–35	45	91
Cumbo-Nacheli 2022, (32)	Retrospective	20	22	SD: 7	20	90
Chen 2021, (33)	Prospective	54	23.2	SD: 10.8	54	82.5
Ekeke 2021, (34)	Retrospective	25	NA	NA	25	96
Chaddha 2019, (35)	Retrospective	165	25	SD: 15	167	77
Rojas-Solano 2018, (36)	Prospective	15	26	Range, 10–63	15	86.7
Galaxy™ Robotic Endoscopy System						
Saghaie 2023, (37)	Abstract Prospective	14	20.5	Range, 10–34	15	93

SD, standard deviation; IQR, interquartile range; NA, not available.

Figure 2 Monarch™ Robotic Endoscopy System bronchoscopy. (A) Tower and cart with robotic arms. (B) Controllers (courtesy of Johnson & Johnson).

robotic arms mounted on the RAB cart (*Figure 2A*). Connecting to the RAB cart, a separate tower houses a monitor screen and a controller (*Figure 2B*). With a 6.0-mm OD for the outer sheath and a 4.2-mm OD with a 2.1-mm ID working channel for the inner bronchoscope, the system prioritizes stability through the outer sheath and enhanced maneuverability and articulation via the flexible inner bronchoscope.

Pre-procedure planning involves a contiguous thin-cut chest CT scan, enabling the creation of a 3D virtual lung reconstruction. The planning software automatically generates pathways to the target, with manual planning available as an alternative. Subsequent registration aligns the robotic bronchoscope's position with the virtual pathway. The Monarch™ platform's registration process entails moving the bronchoscope to the main carina and then retracting it, followed by a prompt to advance and retract the bronchoscope in the contralateral main bronchus, ensuring smooth movement within the airways.

The proprietary navigation algorithm of the Monarch™ system combines optical pattern recognition, electromagnetic navigation (EMN) positioning, and robotic insertion data to confirm the scope tip position within the lung. This fusion process corroborates the signals with the CT-derived airway map. Operators control the bronchoscope using a handheld controller resembling a gaming controller. To compensate for the lack of tactile feedback, the system triggers "buckling errors" upon pressure on the airway walls. Fluoroscopy or rEBUS, as well as CBCT and other intraprocedural imaging devices, are used to verify target reach before locking the entire bronchoscope system in a static position for biopsy acquisition. A comprehensive comparative description of RAB and EMN to the other RAB systems is presented in *Table 2*.

Evidence

In 2018, Rojas-Solano *et al.* conducted the first human safety and feasibility study using the Monarch™ system (36). Out of the 15 lesions studied, 14 (93%) were successfully sampled, without complications. The initial post-market multicenter study by Chaddha *et al.* involved four centers and analyzed 167 PPL in 165 patients (35). With a mean lesion size of 25±15 mm, 71.3% of lesions were ≤30 mm, and 70.7% were located in the peripheral third of the lung. Successful navigation was achieved in 88.6% of cases, with visual confirmation by rEBUS in 84.4% of lesions (concentric =57.5%; eccentric =42.5%). Diagnostic sensitivity was reported at 69.1% *vs.* 77%, considering inflammation alone as non-diagnostic *vs.* diagnostic, respectively (35).

The first prospective multicenter pilot and feasibility study, known as the BENEFIT study, included 54 patients across five different centers, with a median lesion size of 23 mm (IQR, 15–29 mm) (33). Navigational success, assisted by rEBUS, was achieved in 96% of cases, with an estimated diagnostic yield of 74.1%. Stratification by rEBUS view revealed an accuracy of 80.6% for concentric and 70% for eccentric views. The safety profile mirrored that of prior publications, post-procedural pneumothorax occurred in 3.7% (2/54) of patients, one requiring tube thoracostomy (33).

Agrawal *et al.* conducted a retrospective study on factors

Figure 3 The Galaxy System™ comprising of a single platform, arm, screen, and controller (courtesy of Noah Medical).

influencing diagnostic accuracy using the Monarch™ system and rEBUS (38). Evaluating 124 patients with a median PPL size of 20.5 mm, the study reported an 82% navigational success rate and a diagnostic yield of 77% after a 12-month follow-up period. Similar diagnostic yields were observed for concentric (85%) and eccentric views (84%) on rEBUS. Finally, Khan *et al.* published their findings on a large-scale retrospective real-world study, comprising of 264 patients with a median PPL size of 19.3 mm (range, 3.2–72.5 mm) (29). Diagnostic yield achieved was 85.2%, while adverse event rate was 7.6%, including pneumothorax and bleeding.

Recently completed is the TARGET study, a multicenter prospective post-marketing trial, enrolling 1,200 patients across 30 sites undergoing robotic-assisted transbronchial lung biopsy using the Monarch™ platform over a four-year period. The primary endpoint involved the incidence of device or procedure-related complications, while secondary endpoints assessed diagnostic yield and sensitivity for malignancy, procedural details, and post-intervention adverse events, with patient follow-up extending to 24 months (Clinical Trial ID: NCT04182815). A comprehensive summary of findings for Monarch™ is described in *Table 3*.

Galaxy System™

The Galaxy System™ developed by Noah Medical in San Carlos, CA, USA, received United States Food and Drug Administration (FDA) approval in March 2023 (*Figure 3*). It employs a disposable, single-use bronchoscope featuring a 4.0-mm OD, 2.1-mm working channel, and integrated vision capabilities. The navigation system implements EMN in conjunction with integrated tomosynthesis technology and augmented fluoroscopy.

During the navigation process, EMN guides the system to within 2 cm of the target lesion. Subsequently, proprietary digital tomosynthesis, known as Tool in Lesion Technology (TiLT+ Technology™), is employed via a standard fluoroscopy C-arm to confirm the tool's precise placement in relation to the lesion. Digital tomosynthesis, akin to CT scanning, involves capturing a series of X-ray images from various angles to reconstruct a 3D image. Notably, this technique requires fewer images taken from a relatively narrower angle (15–60°), compared to the broader range (180°) employed in CT scans (39). This allows for the use of a standard C-arm instead of a dedicated CT scanner.

Positioning itself as a cost-competitive RAB platform, the Galaxy System™ incorporates a disposable, single-use scope that eliminates the need for reprocessing the scope and contributes to cost savings and procedural turnaround. The system features native fluoroscopy/CBCT integration, also in line of economic benefits. A comprehensive comparative description of RAB with EMN, digital tomosynthesis and TiLT+ to the other RAB systems is presented in *Table 2*.

Evidence

Bhadra *et al.* published the inaugural animal study, titled "The MATCH Study", which explored the application of the Galaxy System™ (40). This study involved four operators conducting navigation and target reach on four pigs. Each physician performed 4 to 6 nodule biopsies for a total of 20 simulated PPL. The average lesion size was 16.3±0.97 mm, predominantly located in the lower lobes (65%). Results revealed a 100% success rate in navigation, a 100% diagnostic yield, and a tool-in-lesion rate of 95%.

Currently, an ongoing clinical trial aims to confirm the accuracy of the TiLT+ incorporated in the Galaxy System™. The trial, with an estimated enrollment of 25 participants, focuses on the primary outcome of successful tool-in-lesion confirmation via CBCT (Clinical Trial ID: NCT06056128). Preliminary results from 15 sampled PPL with a mean size of 20.5 mm were presented in 2023, showing a promising 100% target reach, 86–93% overall diagnostic yield and 3 reported complications (37).

Discussion

Robotic bronchoscopy aims to enhance diagnostic accuracy and safety for pulmonary diagnostic procedures by implementing advanced planning systems for more accurate navigation and biopsy tool delivery, while overcoming the limitations of standard flexible bronchoscopy and percutaneous transthoracic biopsy.

Since its introduction in 2018, RAB has shown increasing diagnostic yields, with observational studies reporting ranges from 76% up to 93% across published literature (*Table 3*). In a meta-analysis including 20 RAB studies, 1,779 PPL were evaluated. Reported pooled diagnostic yield was 84.5%, while complication rates were 2.3% for pneumothorax, 1.2% for pneumothorax requiring chest tube, and 0.5% for bleeding (41). Two recent meta-analyses on guided bronchoscopy, including EMN, virtual bronchoscopy, and RAB, showed overall diagnostic accuracies of 69.4% [95% confidence interval (CI): 67–71.1%, 126 studies] and 70.9% (95% CI: 68.4–73.2%, 95 studies) (42,43). For RAB specifically, diagnostic yield was 77.6% (43) and 77.3% when combined with CBCT (42), the highest yield among all procedures in both analyses. Adverse events rates remained at 2% for pneumothorax requiring intervention and for bleeding (42,43).

While these meta-analyses have compared RAB to other bronchoscopic approaches, there is virtually no data directly comparing RAB systems, and scarce analysis between RAB and non-bronchoscopic techniques. Computed tomography-guided transthoracic biopsy (CTTB) has historically been the gold standard for diagnosing PPL, consistently demonstrating yields over 80% (44-46). However, its diagnostic performance is hindered by significant rates of pneumothorax and bleeding, ranging from 6–15% and 18%, respectively (47,48). For RAB, Monarch™ has reported pneumothorax rates from 0–5.7% (29,30,33,35). This pneumothorax occurrence was lower in comparison to other published studies involving PPL sampling through standard flexible bronchoscopy and EMN (49,50). With the Ion™ system, the pneumothorax rates have ranged from 0–7% (6-9,12,13,19). The incidence of substantial airway bleeding following conventional transbronchial biopsy is estimated to be around 2–3% of cases (49,50). The Monarch™ Platform has disclosed airway bleeding rates from 0–3.2% (28-30,35). Likewise, the Ion™ system has exhibited low airway bleeding occurrence, ranging from 0% to 0.8% (6-8,20,51). To date, there are no published data on procedure-related adverse events using the Galaxy System™.

In 2023, a retrospective comparative analysis between ssRAB and CTTB by Yu Lee-Mateus *et al.* revealed similar diagnostic yields (87.6% and 88.4%, respectively) with significantly lower complication rate for ssRAB (4.4% *vs.* 17%, P=0.001) (19). The same authors later presented an updated assessment between both procedures focused on subsolid nodules, reconfirming comparable diagnostic performances, 85.7% for ssRAB and 89.5% for CTTB, and fewer complications for the robotic approach (7.4% versus 21.2%, respectively) (13). Compared to CTTB, bronchoscopic procedures do not involve puncturing through the chest wall and lung parenchyma to reach PPL, which inherently increases the risk of pneumothorax and bleeding. In contrast to other bronchoscopic approaches, RAB has the advantages of pre-procedural planning based on contiguous thin-cut CT to create a 3D reconstruction of the airway, navigational plan towards the virtual target, live feedback on distance to target and pleura, and a stable robotic arm with thinner working channel that allows for farther reach and interchangeable biopsy tools. These characteristics enable more accurate sampling and consequently, enhance the safety profile of RAB. As robotic bronchoscopy expands worldwide, further research directly comparing RAB systems and against non-bronchoscopic techniques is needed to ascertain the optimal diagnostic procedure for PPL. An upcoming systematic review and network meta-analysis assessing diagnostic accuracy and safety of navigational guided bronchoscopy, including RAB, and CTTB (PROSPERO ID: CRD42023432829) and two ongoing clinical trials facing RAB to CTTB (Clinical Trial ID: NCT04250194) and to standard EMN (Clinical Trial ID: NCT06308120) aim to answer this question.

One significant challenge impacting precise bronchoscopic navigation and sampling is computed-tomography-to-body divergence (CTBD). Regardless of the robotic platform used, target location and navigational planning relay on pre-procedural CT. These capture lung volumes nearing total lung capacity, at full inspiration on breath hold, which differs from the patient's lung volumes during the procedure under general anesthesia and paralysis, controlled mechanical ventilation, and closer to functional residual capacity (52). Additionally, atelectasis may occur during general anesthesia, particularly in the lower lobes, as well as other factors such as mucus plugging, pleural effusions, bleeding, etc. that can cause structural distortions (39). CTBD originates from the difference between the location of the virtual target from pre-procedural CTs and the real-

time intraprocedural location, which has been reported up to a median of 17 mm (52,53). The three robotic bronchoscopy platforms utilize intraprocedural imaging systems to mitigate CTBD. Ion™ Endoluminal is supported by standard CBCT and mCBCT with the Cios Spin (Cios Spin, Siemens Healthineers, Siemens Medical Solutions, USA). CBCT uses a cone-shaped X-ray beam projecting onto a flat panel detector that is able to produce 3D images with a reconstruction algorithm, to be reviewed during the procedure for assessment of the robotic tip location in relation to the target lesion for potential readjustment. mCBCT functions in a similar manner, implementing the concepts of X-ray based tomosynthesis, able to produce images similar to conventional fixed CBCT, as well as 2D X-ray fluoroscopic images and 3D reconstructions, although not suitable for augmented fluoroscopy (39). With CBCT, Ion™ Endoluminal has reported diagnostic yields of 86% and 91.4% (7,9). In a retrospective study on 30 nodules using ssRAB and mCBCT, divergence, defined as a distance greater than 10 mm between the target location in pre-procedure CT and the time of procedure, was found in 50% of cases (20). With mCBCT, which also allows for correction of the navigation plan to the real-time location (39,54), the virtual pathway and biopsy tool were readjusted when necessary and diagnostic yield achieved was 93% (20). Monarch™ has used standard CBCT as well as LungVision™ (Body Vision Medical Ltd., Ramat Ha Sharon, Israel), a system that combines augmented fluoroscopy with artificial intelligence to generate a navigational pathway from pre-procedure CT and real-time fluoroscopy (52). With LungVision™, diagnostic accuracy surpassed 90% in a study with 45 patients (31), while with CBCT, sensitivity for malignancy achieved was 86% in 20 lesions (32). The Galaxy System™ integrates digital tomosynthesis, which relays on computer-based reconstruction algorithms to produce radiographic images with depth of field from multiple single-plane X-ray images over angles as small as 50° and augmented fluoroscopy (39), using standard C-arm CT. As described previously, an animal study assessing reach and feasibility achieved tool-in-lesion confirmation in 95% of cases, and diagnostic yield of 100% (40). The preliminary results of the first human study reported 100% target reach and approximately 90% of overall diagnostic yield (37).

The reliability and precision of RAB have evolved into potential applications in therapeutic bronchoscopy. RAB has been used for the direct injection of liposomal amphotericin B into a chronic *Aspergillus* lesion, with subsequent radiological and clinical improvement (55). Zhong *et al.* documented the application of RAB in conjunction with photodynamic therapy for a patient with adenoid cystic carcinoma, involving the entire tracheal wall and resulting in lumen obstruction (56). Exploring the administration of chemotherapy and other agents through direct intra-tumoral injection is currently under consideration (57). This strategy seeks to boost immunotherapy directly within the local tumor microenvironment. RAB may play a crucial role in facilitating nodule marking during the perioperative phase for minimally invasive thoracic surgery, to improve accuracy in localization and resection with negative margins based on the dyes and dye-soaked coils luminescence (58,59). Currently, active clinical trials are in progress to test direct endobronchial ablation (Clinical Trial ID: NCT05299606; Clinical Trial ID: NCT05890872) for local treatment of lung primary and metastatic malignancies.

Addressing competency and skill acquisition for patient safety in the context of advanced robotic bronchoscopy encounters obstacles related to equipment costs, skill acquisition challenges, and overcoming the learning curve for widespread adoption. Tackling these issues requires the implementation of structured training programs that provide thorough education on both equipment operation and procedural techniques. To mitigate variability in the learning curve, standardized training modules and mentorship programs can assist practitioners in mastering skills consistently. Furthermore, enhancing access requires collaborative efforts among institutions to share expertise and resources, potentially through specialized training centers or virtual platforms. The challenge of conducting a cost-to-benefit analysis remains, as average costs for robotic bronchoscopy plus secondary imaging equipment are over six-figure United States dollars, respectively, in addition to all device-specific tools (39). Comprehensive studies to assess overall cost-effectiveness and clinical impact are crucial for making informed decisions regarding resource allocation and promoting broader accessibility of this technology to enhance patient care.

Strengths and limitations

This narrative review aims to summarize the findings on RAB and present a comprehensive comparison of the three approved systems. We acknowledge the nature of the narrative review may limit an exhaustive systematic review approach and most of the data described comprised

retrospective or observational prospective studies.

Conclusions

Robotic bronchoscopy, comprised by the Ion™, Monarch™, and Galaxy™ systems, represents an advancement in lung cancer diagnostics. These technologies demonstrate effective diagnostic performance with low complication rates. As RAB continues to expand worldwide, RAB may soon allow a "one-stop shop" approach with diagnosis, staging, and treatment within the same procedure.

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Footnote

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