Original Article

Electromagnetic navigation bronchoscopy-guided preoperative lung nodule localization in video-assisted thoracic surgery (VATS): a learning curve analysis

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Background: Electromagnetic navigation bronchoscopy (ENB) has been widely used to mark small peripheral pulmonary nodules (PPNs) in video-assisted thoracic surgery (VATS) resection. This technique offers the advantages of a high accuracy and fewer complications. However, few studies have analyzed the learning curve of ENB-guided preoperative localization. We aimed to describe the learning curve and factors influencing ENB-guided thoracoscopic pulmonary nodule resection.

Methods: This study included 300 consecutive patients with PPNs who underwent ENB-guided localization by the same endoscopist in our department between November 2019 and December 2021. The cumulative sum (CUSUM) method was used to analyze the learning curve of ENB-guided localization and the learning curve in different lobes, while logistic regression was used to analyze the risk factors affecting ENB operative time (OT).

Results: In 184 patients with 300 nodules, three learning phases were identified through turning points of the learning curve: Phase I (the 16th nodule), Phase II (the 17th to the 107th nodule), and Phase III (the 107th to the 300th nodule). No significant difference was found in the success rate of ENB-guided localization in each phase of the learning curve (100%, 96.7%, and 97.9%, P=0.78). The distance from the localization to the pleura in Phase I was statistically significantly shorter than that in Phase II and Phase III (0.6±0.4 *vs.* 1.1±0.6 *vs.* 1.0±0.5 cm, P=0.001 and P=0.003). Furthermore, the learning curves for nodules in different lobes were different. The learning curve for the upper lobe nodules was divided into two phases; the learning curve for the middle lobe disclosed more negative values; and the learning curve for the lower lobe nodules displayed no obvious pattern. Significant differences were found in nodule location, distance from the localization to the pleura and learning curve phase (P=0.003, P<0.001, P=0.02). The independent factors for OT included gender, smoking history, nodule type, distance from localization to the pleura, and learning curve phase.

Conclusions: ENB OT at the 107th nodule leveled off and showed a downward trend. Different lobes have different learning curves, the middle lobe is the easiest lobe to learn with ENB and can be used as the first lobe of choice for beginners. The learning curve can objectively evaluate the accuracy of ENB location and help endoscopists identify areas for improvement.

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Keywords: Electromagnetic navigation bronchoscope (ENB); peripheral pulmonary nodules (PPNs); video-assisted thoracoscopic surgery (VATS); learning curve; cumulative sum (CUSUM)

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Introduction

Lung cancer is a malignant tumor with the highest mortality rate worldwide. About 1.8 million people succumb to lung cancer every year (1). In China, lung cancer currently occupies the top in morbidity and mortality (2). With the widespread application of low-dose computed tomography (CT) scans, an increasing number of nodules have been identified, particularly ground-glass nodules (GGNs). The NELSON lung cancer screening study found that lung cancer mortality was significantly lower among those who underwent volume CT screening than among those who did not (3). Surgical resection is the gold standard for treating patients with peripheral pulmonary nodules (PPNs) suspected of lung cancer on CT. Accurate detection of small nodules using video-assisted thoracic surgery (VATS) has been proven difficult, especially for nodules smaller than 10 mm. Deep, small, GGNs have also been difficult to detect during VATS, which may lead the surgeon to remove more lung tissue or refer to thoracotomy to attempt bimanual palpation to successfully resect the lesion (4).

Electromagnetic navigation bronchoscopy (ENB) consists of a field generator that generates an electromagnetic field, in addition to a locatable guide (LG) probe. When the LG probe is inserted into a magnetic field, it generates a voltage of which the magnitude and polarity reflect the probe's position and orientation in the electromagnetic field (5). ENB is safe, feasible, and effective for VATS intraoperative localization (6,7). Currently, commonly used ENB-guided localization methods include vector positioning (8), methylene blue massage positioning (9), and indocyanine green (ICG) fluorescent dye (10). Compared with CT-guided hook-wire and methylene blue localization, the failure rate and incidence of pneumothorax are lower with ENB-guided localization (11,12). Without CT guidance, the procedure can be performed in the operating room without radiation exposure. However, few articles have discussed the learning curve of ENB-guided localization in VATS peripheral nodule resection (13). There is a paucity of research on the learning curves of different lobes. Therefore, we reviewed the case of the same endoscopist in our department who performed ENB to locate the PPNs. This study used the cumulative sum (CUSUM) technique to analyze the learning curve of the ENB-guided preoperative localization. We present this article in accordance with the STROBE reporting checklist (available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-337/rc).

Highlight box

Key findings

- This study uses the cumulative sum method to analyze the learning curve of electromagnetic navigation bronchoscopy (ENB) localization and the learning curve in different lobes, use logistic regression to analyze the risk factors affecting ENB operative time (OT).

What is known and what is new?

- Learning curve of ENB in the localization of peripheral pulmonary nodule can improve the endoscopist to better understand the problems with the operation, which is of guiding significance for us to master ENB-guided localization.
- Three learning phases were identified through turning points of the learning curve in 184 patients with 300 nodules, the learning curves for nodules in different lobes were different. The independent factors for OT included gender, smoking history, nodule type, distance from localization to the pleura, and learning curve phase.

What is the implication, and what should change now?

- The beginners to prioritize nodules in the middle lobe as their first choice. Male and current smokers may need a shorter OT, but require a longer OT for the distance from localization to the pleura in the lower lobe because of computed tomography-to-body divergence. We will investigate how to improve intraoperative atelectasis and reduce the discrepancy.

Methods

Patients and inclusion criteria

Between November 2019 and December 2021, 184 patients underwent ENB-guided preoperative localization

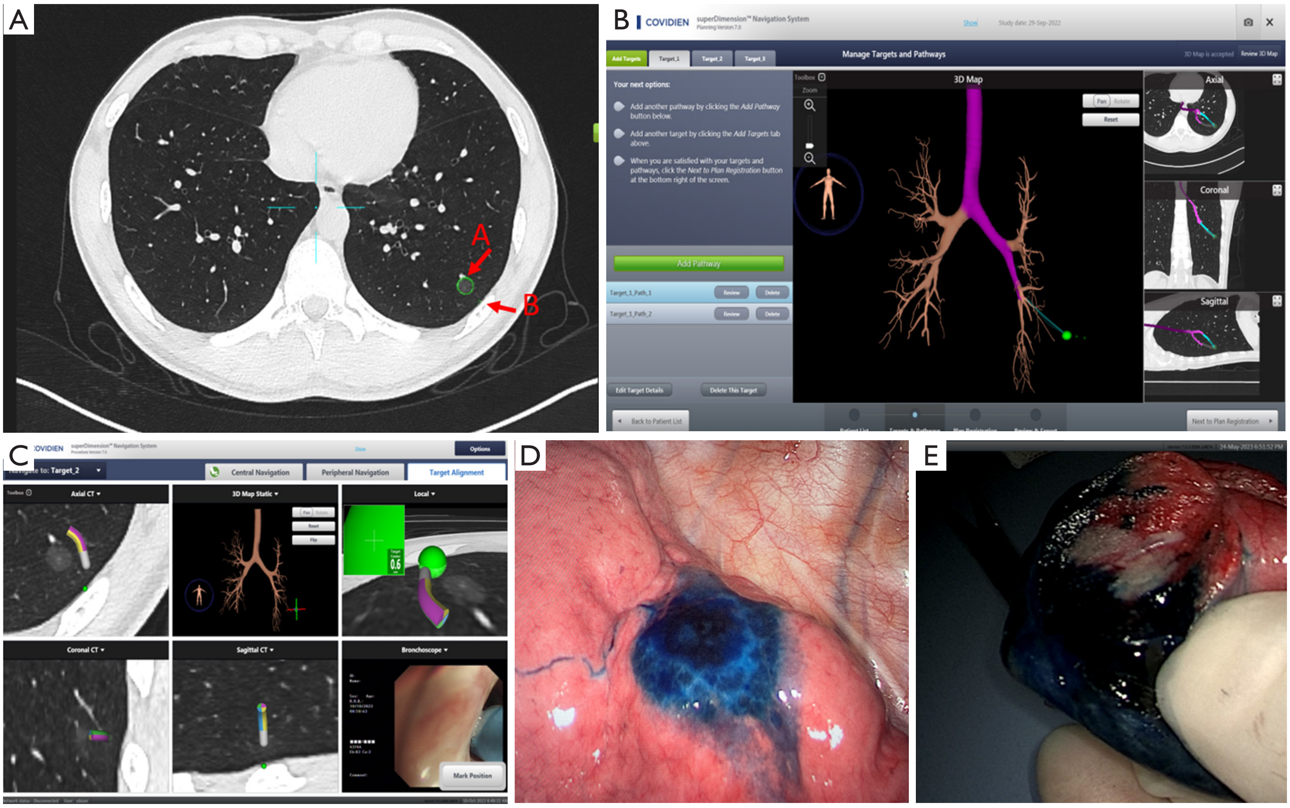

Figure 1 The procedure of ENB-guided localization PPNs in VATS. (A) Target lesion A was a peripheral lung lesion suspected of lung cancer on the CT scan. The shortest distance from the lesion A to the pleura B was used as the methylene blue marker. The green circle as a marker for the lesion on the electromagnetic navigation equipment. (B) The bronchial tree was reconstructed using the ENB system, and the pathway was planned for the lesion A and the pleura B. (C) The ENB system guides the LG probe in reaching the lesion and pleura. The distance from the LG probe to the pleura was defined as the distance from the localization to the pleura. The distance from the location to the pleura was 0.5 cm. (D) The pleura was stained blue with methylene blue. (E) The blue-stained area was resected and the lesion was found in that area. ENB, electromagnetic navigation bronchoscopy; PPNs, peripheral pulmonary nodules; VATS, video-assisted thoracic surgery; CT, computed tomography; LG, locatable guide.

PPNs in the Department of Thoracic Surgery of The Second Affiliated Hospital (Tangdu Hospital) of Air Force Medical University. No auxiliary equipment, such as radial endobronchial ultrasound (R-EBUS) or fluoroscope, was used during the surgery. The patient inclusion and exclusion criteria were as follows. Inclusion criteria: (I) PPNs, (II) diameter of pure ground-glass nodules (pGGNs) ≤3 cm, the diameter of mixed ground-glass nodules (mGGNs) ≤2 cm, (III) no pleural depression, (IV) no bronchial ventilation, and (V) chest CT considered adenocarcinoma in situ (AIS), micro invasive adenocarcinoma (MIA), or CT considered invasive adenocarcinoma but unable to tolerate lobectomy. Exclusion criterion: preoperative bronchoscopy showed that the diameter of the grade 6 bronchus was less than 2 mm, and that the extended working channel (EWC) could not be inserted. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This study was approved by the Ethics Committee of The Second Affiliated Hospital of Air Force Military Medical University (No. K202208-10), and informed consent was obtained from the patients and their families for all studies.

Pathway planning and ENB-guided localization

Pathway planning and ENB-guided localization were performed as follows (*Figure 1*):

❖ Pathway planning: low-dose CT scan of the chest recorded in the DICOM format, virtual bronchus reconstruction with the ENB system (Super Dimension, Medtronic, Minnesota, USA), determination of the target lesion, and identification of the pathway to the target lesion.

- ENB-guided localization: the patient lied on the operating bed and was located in the magnetic field, and general anesthesia with laryngeal mask anesthesia, electromagnetic navigation EWC and LG were inserted through the bronchoscope (BF-1T260, Olympus, Tokyo, Japan) biopsy channel. Next, the registration was completed, and the EWC and LG were navigated to the target and the lesion corresponding to the pleura. Subsequently, the LG was pulled to the trachea and sent to the target again while ensuring that the position was unchanged. Then, a pre-fill catheter with 0.2–0.3 mL of methylene blue was injected into the EWC to mark the pleura. Subsequently, 20–40 mL air was injected to diffuse methylene blue. The LG was sent to the target again to confirm that its position remained unchanged after injecting of methylene blue and air.

Operation

General anesthesia was administered using a double-lumen tube. With the patient in the appropriate lateral decubitus position, three-port or single-port thoracoscopic surgery was performed. The methylene blue-stained area was located and wedge resection (margin ≥2 cm from the lesion) was performed. Based on the intraoperative frozen pathology results, additional segmentectomy or lobectomy with lymph node dissection was performed.

Operative time (OT)

The OT was considered to begin when the ENB registration was successfully matched, and the end time was when the pleura was reached and methylene blue was injected. Registration time was not included in the OT because multiple nodules required only one registration. The registration time was estimated as 47–276 s.

ENB location success and failure

ENB-guided localization was considered successful when methylene blue staining was observed on the pleura and lesions were found in the resected lung tissue. ENB-guided localization was considered a failure when no methylene blue staining was observed on the pleura during thoracoscopy, when methylene blue staining was observed on the pleura but no lesions were found in the resected lung tissue, or when no methylene blue staining was found in the lung.

Statistical analysis

In our statistical analysis, we drew a learning curve using the CUSUM technique. The formula used in this study is as follows:

$$\mathrm{CUSUM}_{\mathrm{OT}} = \sum_{i=0}^{n}(xi - \mu) \quad [1]$$

where *xi* represents the actual OT of each nodule (i=1), μ represents the average OT of all nodules, and *n* represents the operation sequence number. The positioning OT of the ENB was used as the evaluation index, and the mean OT was used as the target value. The difference between the actual OT and the mean OT of each patient was accumulated and summed as the ordinate, and the operation sequence was the abscissa (14). Microsoft Excel 2016 (Microsoft Corp., Redmond, WA, USA) was used to construct the learning curves. The OT of navigation system was estimated based on the learning curve of the second phase. The average value was 20 min, and the 300 nodules were divided into ≤20 and >20 min groups according to the localization time. SPSS 26.0 (IBM, Armonk, New York, USA) was used for univariate and logistic binary regression analyses. Statistically significant was set at $P<0.05$.

Results

General characteristics

A total of 184 patients with 300 nodules were included in this study. The mean age was 54.2±12.0 years, ranging from 27 to 82 years. The study included 66 males (35.9%) and 118 females (64.1%), 107 single nodules (58.2%) and 77 multiple nodules (41.8%), 13 solid nodules (4.3%), 124 mGGNs (41.3%), and 163 pGGNs (54.3%). There were 168 nodules in the upper lobe (56.0%), 26 nodules in the middle lobe (8.7%), and 106 nodules in the lower lobe (35.3%). The maximum diameter of the nodules range 3–22 mm and the mean diameter was 8.22±3.06 mm. The shortest distance from the lesion to the pleura was 0.91±0.7 cm. The localization time was 3–81 min, and the average time was 17.11±14.0 min (*Table 1*).

Table 1 General characteristics

Characteristics	Values
No. of patients	184
Gender	
Male	66 (35.9)
Female	118 (64.1)
Smoke	
Smoker	14 (7.6)
Former smoker	18 (9.8)
Non-smoker	152 (82.6)
Type of nodule	
Solitary nodule	107 (58.2)
Multiple nodules	77 (41.8)
Nodules (n=300)	
Size of nodule (mm)	8.22±3.06
Distance from localization to pleura (cm)	0.91±0.7
OT (min)	17.11±14.0
Nodule location	
Upper lobe	168 (56.0)
Middle lobe	26 (8.7)
Lower lobe	106 (35.3)
Nodule component	
Solid nodules	13 (4.3)
mGGN	124 (41.3)
pGGN	163 (54.3)
Resection	
Unresected	3 (1.0)
Wedge resection	271 (90.3)
Sub-segmentectomy	3 (1.0)
Segmentectomy	11 (3.7)
Lobectomy	12 (4.0)
Pathology	
Unresected	3 (1.0)
AAH	32 (10.7)
AIS	160 (53.3)
MIA	34 (11.3)
IA	17 (5.7)
Benign	51 (17.0)
Else	3 (1.0)
Successful location	
Failure	7 (2.3)
Success	293 (97.7)

Data are presented as n (%) and mean ± SD. OT, operative time; mGGN, mixed ground glass nodule; pGGN, pure ground glass nodule; AAH, atypical adenomatous hyperplasia; AIS, adenocarcinoma in situ; MIA, micro invasive adenocarcinoma; IA, invasive adenocarcinoma; SD, standard deviation.

Localization failure and complications

In total, 293 nodules were successfully localized (97.7%), while 7 nodules failed to localize (2.3%), including 5 nodules in the lower lobe and two nodules in the upper lobe. In addition, 297 nodules (99.0%) were surgically resected, and 3 nodules (1.0%) were not resected after localization failure, because there were multiple nodules on the same side, and the nodule was too small. Complications related to the ENB-guided localization procedure occurred in two patients: one case of pneumothorax occurred when the middle lobe of the right lung was located in the horizontal fissure, and the other case of pneumothorax occurred when the lower lobe of the right lung was located in the dorsal segment. None of the patients experienced any bleeding complications.

Learning curve analysis

The difference between the localization OT and average localization OT was positive, indicating that the ENB was in the learning phase. On the other hand, a negative difference indicated that the ENB had mastered. We plotted the OT of the 300 nodules in chronological order, and the CUSUM method was used to analyze the learning curve of OT in ENB-guided localization (*Figure 2*). The learning curve was divided into three phases: Phase I, the learning phase (the 16th nodule); Phase II, the mastery phase (the 17th to the 107th nodule); Phase III, the stable learning phase (the 107th to the 300th nodule).

Factors affecting different learning phases

Significant differences were noted in the distance from the localization to the pleura in the three phases (P=0.04), with Phase I injected methylene blue closer to the pleura (I *vs.* II, P=0.001, II *vs.* III, P=0.003). We found significant differences

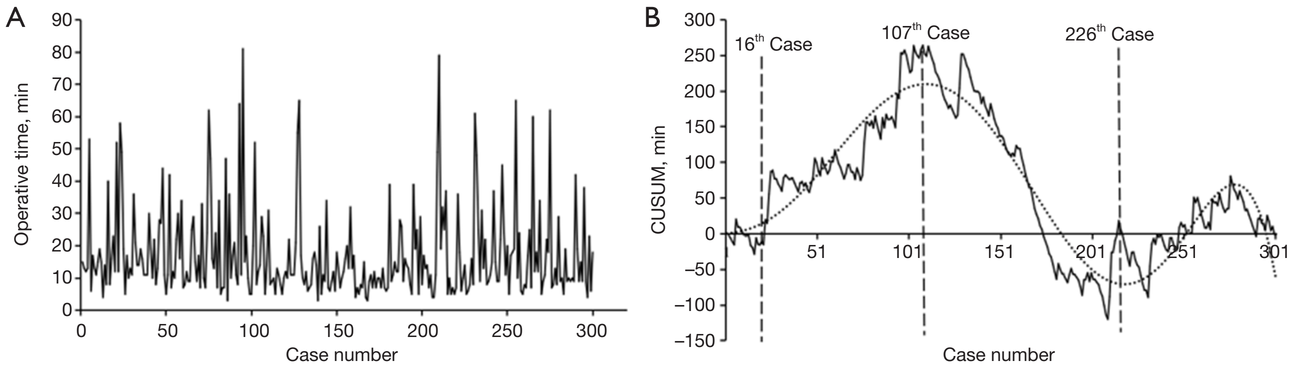

Figure 2 OT and learning curve of 300 nodules. (A) ENB-guided preoperative localization OT is presented in chronological order. (B) The learning curve of ENB-guided PPN localization using the CUSUM method for OT was analyzed. CUSUM, cumulative sum; OT, operative time; ENB, electromagnetic navigation bronchoscopy; PPN, peripheral pulmonary nodule.

in nodule components in different learning phases (P=0.001) and differences between the groups in nodule components in different learning phases (I *vs.* II: P=0.008, II *vs.* III: P=0.03). There were more pGGNs in Phase II and mGGNs in Phase III. We found a between-group difference in smoking between Phases I and III, with more non-smoking patients in Phase III (P=0.04). Besides, we observed an intergroup difference in the navigation time between Phases II and III (P=0.01), which was longer in Phase II (*Table 2*).

Influencing factors of OT

There were significant differences in OT in nodule location, distance from the localization to the pleura, and learning curve phases (P=0.003, P<0.001, and P=0.02, respectively). Multivariate logistic binary regression analysis revealed that gender, smoking history, nodule type, distance from localization to the pleura, and learning curve phases were independent factors influencing OT. Distance from the localization to the pleura [odds ratio (OR) =12.297; 95% confidence interval (CI): 5.673–26.657; P<0.001] and learning curve Phase I (OR =11.591; 95% CI: 2.745–48.941; P=0.001) were risk factors for OT ≤20 min, whereas male gender (OR =0.394; 95% CI: 0.169–0.920; P=0.03), smoking history (OR =0.1040; 95% CI: 0.014–0.781; P=0.03), and solitary nodules (OR =0.372; 95% CI: 0.186–0.746; P=0.005) were protective factors for OT ≤20 min (*Table 3*).

Learning curves corresponding to different lobes (Figure 3)

The upper lobe learning curve showed that the cutoff point at the 79th nodule was divided into two phases: Phase I (the 79th nodule) was the learning improvement phase, and Phase II (the 79th to the 157th nodule) was the mastery phase. No obvious cutoff point was found for the middle lobe learning curve, and the cumulative time was lower than the average. Lower lobe learning had a cutoff point at the 7th and 37th nodules, but it fluctuated greatly in the later period without a clear pattern.

Discussion

CUSUM analysis calculates the average value of the collected data and adds them to the continuous deviations from the average value. The change in the CUSUM can sensitively reveal changes in the average value or trend of the baseline data (14), objectively and quantitatively evaluate the surgical learning curve, and allow the endoscopist to improve the operation through the learning curve (15). There is less of a learning curve associated with ENB in the localization of PPN resection. The differences in learning and proficiency in ENB procedures can be detected by learning curves, which allow the endoscopist to better understand the problems with the operation, which is of guiding significance for us to master ENB-guided localization.

The CUSUM method was used to analyze the learning curves of 300 nodules. The learning curve displayed a downward trend after the 107th nodule. Shi *et al.* (13) reported that the learning curve of ENB-guided localization showed a continuous downward trend after the 47th case, and nodules without bronchial ventilation signs were more difficult to locate using ENB than those with bronchial ventilation

Table 2 Clinical characteristics at different phases of the learning curve

Characteristics	Phase I	Phase II	Phase III	P	P1 (I *vs.* II)	P2 (I *vs.* III)	P3 (II *vs.* III)
Age (years)	54.1±11.8	51.7±11.7	54.7±12.1	0.26	>0.99	>0.99	0.30
Gender				0.76	0.53	0.54	0.97
Male	6 (46.2)	21 (35.0)	39 (35.1)				
Female	7 (53.8)	39 (65.0)	72 (64.9)				
Smoke				0.07	0.11	0.04	0.37
Non-smoker	8 (61.5)	50 (83.3)	94 (84.7)				
Former smoker	4 (30.8)	7 (11.7)	7 (6.3)				
Smoker	1 (7.7)	3 (5.0)	10 (9.0)				
Nodule type				0.23	0.36	0.12	0.34
Solitary nodule	10 (76.9)	37 (61.7)	60 (54.1)				
Multiple nodules	3 (23.1)	23 (38.3)	51 (45.9)				
Size of nodule (mm)	9.2±2.3	8.1±2.7	8.2±3.3	0.43	0.20	0.21	0.87
Nodule component				0.001	0.008	0.03	<0.001
pGGN	9 (56.3)	72 (79.1)	82 (42.5)				
mGGN	4 (25.0)	18 (19.8)	102 (52.8)				
Solid nodules	3 (18.7)	1 (1.1)	9 (4.7)				
Nodule location				0.62	0.32	0.28	0.98
Upper lobe	8 (50.0)	52 (57.1)	108 (56.0)				
Middle lobe	0 (0.0)	8 (8.8)	18 (9.3)				
Lower lobe	8 (50.0)	31 (34.1)	67 (34.7)				
OT (min)	16.8±12.5	20.1±15.5	15.7±13.2	0.050	0.38	0.78	0.01
Pathology				0.53	0.74	0.86	0.23
Unresected	0 (0.0)	1 (1.1)	2 (1.0)				
AAH	3 (18.7)	10 (11.0)	19 (9.8)				
AIS	8 (50.0)	43 (47.3)	109 (56.5)				
MIA	1 (6.3)	17 (18.7)	16 (8.3)				
IA	1 (6.3)	5 (5.5)	11 (5.7)				
Begin	3 (18.7)	15 (16.4)	33 (17.1)				
Else	0 (0.0)	0 (0.0)	3 (1.6)				
Successful location				0.79	>0.99	>0.99	0.68
Success	16 (100.0)	88 (96.7)	189 (97.9)				
Fail	0 (0.0)	3 (3.3)	4 (2.1)				
Distance from the localization to the pleura (cm)	0.6±0.4	1.1±0.6	1.0±0.5	0.004	0.001	0.003	0.34

Data are presented as mean ± SD, n (%). pGGN, pure ground glass nodules; mGGN, mixed ground glass nodule; OT, operative time; AAH, atypical adenomatous hyperplasia; AIS, adenocarcinoma in situ; MIA, micro invasive adenocarcinoma; IA, invasive adenocarcinoma; SD, standard deviation.

Table 3 Influencing factors associated with OT

Characteristics	OT		Univariate	Multivariate	
	≤20 min	>20 min	P	OR (95% CI)	P
Age (years)	55±11.6	51.9±12.3	0.054	0.991 (0.963–1.021)	0.56
Gender			0.70		0.03
Male	71 (31.4)	25 (33.8)		0.394 (0.169–0.920)	
Female	155 (68.6)	49 (66.2)		1.000	
Smoke			0.21		0.01
Non-smoker	190 (84.1)	67 (90.5)		1.000	
Former smoker	20 (8.8)	2 (2.7)		1.338 (0.298–6.003)	0.70
Smoker	16 (7.1)	5 (6.8)		0.104 (0.014–0.78)	0.03
Nodule type			0.12		0.005
Solitary nodule	75 (33.2)	32 (43.2)		0.372 (0.186–0.746)	
Multiple nodules	151 (66.8)	42 (56.8)		1.000	
Nodule component			0.80		0.91
pGGN	123 (54.4)	40 (54.1)		1.208 (0.203–7.204)	0.84
mGGN	92 (40.7)	32 (43.2)		1.172 (0.560–2.454)	0.67
Solid	11 (4.9)	2 (2.7)		1.000	
Nodule location			0.003		0.22
Upper lobe	131 (58.0)	37 (50.0)		5.815 (0.606–44.349)	0.13
Middle lobe	25 (11.0)	1 (1.4)		3.442 (0.412–28.788)	0.25
Lower lobe	70 (31.0)	36 (48.6)		1.000	
Pathology			0.41		0.08
Unresected	2 (0.9)	1 (1.4)		1.000	
AAH	28 (12.4)	4 (5.4)		1.666 (0.038–72.423)	0.79
AIS	117 (51.8)	43 (58.1)		0.091 (0.004–2.000)	0.13
MIA	25 (11.1)	9 (12.2)		0.570 (0.033–9.858)	0.70
IA	11 (4.9)	6 (8.1)		1.037 (0.052–20.611)	0.98
Benign	41 (18.1)	10 (13.5)		0.880 (0.039–19.855)	0.94
Else	2 (0.9)	1 (1.4)		0.375 (0.019–6.867)	0.50
Size of nodule (mm)	8.1±3.0	8.5±3.2	0.47	1.049 (0.942–1.169)	0.38
Distance from localization to pleura (cm)	0.9±0.4	1.5±0.6	<0.001	12.297 (5.673–26.657)	<0.001
Phase			0.02		0.002
I	14 (6.2)	2 (2.7)		11.591 (2.745–48.941)	0.001
II	59 (26.1)	32 (43.2)		2.172 (1.010–4.667)	0.047
III	153 (67.7)	40 (54.1)		1.000	

Data are presented as mean ± SD, n (%). OT, operative time; OR, odds ratio; CI, confidence interval; pGGN, pure ground glass nodules; mGGN, mixed ground glass nodule; AAH, atypical adenomatous hyperplasia; AIS, adenocarcinoma in situ; MIA, micro invasive adenocarcinoma; IA, invasive adenocarcinoma; SD, standard deviation.

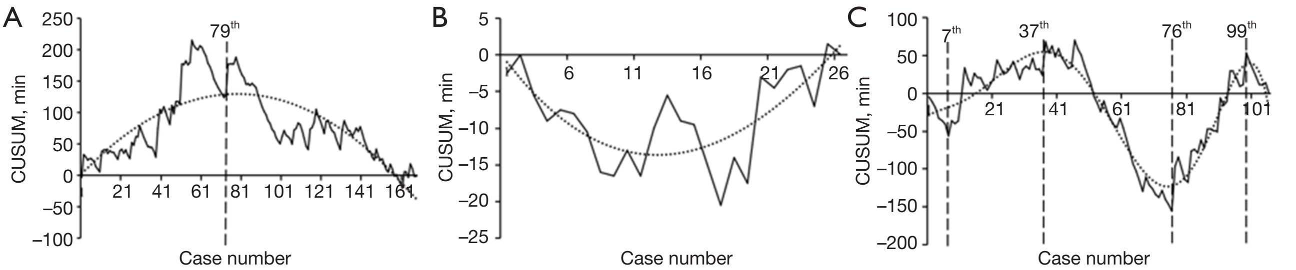

Figure 3 Learning curve of different lobes. (A) The upper lobe learning curve. (B) The middle lobe learning curve. (C) The lower lobe learning curve. CUSUM, cumulative sum.

signs. Toennesen and colleagues (16) demonstrated that, in the learning curve of ENB biopsy by different doctors, the location of lesions was related to the number of cases on the learning curve, and the more peripheral lesions were reached, the more cases were needed for the learning curve. In our study, the lesions had no bronchial ventilation signs, and there was approximately 1 cm from the nodules to the pleura, which aggravated the difficulty of ENB-guided localization and resulted in many cases requiring mastery of the ENB-guided localization. In patients without bronchial ventilation signs, there was a longer learning period during the process of locating the pleura using ENB. Consequently, beginners learning ENB-guided localization are recommended to select nodules with bronchial ventilation signs or closer to the bronchus for easier localization.

The success rate of ENB-guided localization in the three phases of the learning curve showed no difference between the groups, and the success rate of ENB-guided localization in Phase I (100%) was high. This was linked to the selection of easier cases in Phase I, in which the lesions could be removed if ENB-guided localization staining failed. The proportion of pGGNs and mGGNs was lower in Phase I (5.5%, 3.2%), with mastery of ENB-guided localization and publication of the clinical trial results of JCOG0804 (17). Many GGNs have been used for ENB-guided localization. The pGGNs in Phase I of the learning curve were significantly different from those in Phases I and III, whereas the mGGNs were predominant in Phase III, suggesting that the operator gradually increased the difficulty in the learning process. Differences were found between the phases in the nodule component of the learning curve, which was in accordance with the normal learning rule. Beginners learning ENB-guided localization are recommended to select nodules with more solid components. Even if the ENB-guided localization fails, the surgeon can touch the nodule to ensure the success of the surgery and accumulate experience. With the mastery of ENB positioning technology, mGGNs or pGGNs can be located close to the anatomical structure. If localization fails, a large area of lung tissue can also be removed by anatomical location to successfully resect the lesion. As the second stage of the learning curve, it is not advisable to select the large GGNs located at a considerable distance from the pleura, because the greater the spatial gap between the nodule and pleura, the more pronounced the discrepancy in ENB positioning due to potential inaccuracies in ENB-guided localization. In Phase III, as the ENB-guided localization matures, larger GGNs can be used for positioning. Beginners can learn from our experience to improve the success of positioning and gradually select nodules that are difficult to locate to master ENB. In Phase I, the LG probe was closer to the pleura, which was also due to a lack of experience. The average distance from the pleura was 1.1±0.6 to 1.0±0.5 cm with the mastery of ENB-guided localization. The OT in Phase II was longer than that in the other phases, which is in accordance with the characteristics of the learning curve. As the technology was mastered, the time spent in Phase III was shortened.

Nodule location, different learning curve phases, and the distance from the localization site to the pleura were factors influencing OT. Multivariate analysis revealed that the distance from the localization to the pleura was a risk factor for OT. To achieve a more accurate localization, the closer the distance to the pleura, the more accurate the localization. Therefore, the farther the staining is from the pleura, the longer it takes to position the ENB closer to the pleura. There was a positive correlation between OT and the distance from the localization to the pleura; accordingly, the distance from the localization to the pleura is a risk factor for OT. With mastery of ENB, OT is longer in the early learning phase. Phase I of the learning curve was a risk factor for OT, consistent with the rule of the learning curve. Some male patients smoked, while female patients did not; accordingly, male patients included all smokers. Unexpectedly we found that male gender and current smoking were protective factors against OT. Contrary to our results, Shi *et al.* (13) reported that the OT of males was longer than that of females. At present, we do not know why OT is shorter in males and current smokers, perhaps because smoking causes emphysema, and emphysema patients are less prone to anesthesia atelectasis (18).

The learning curve of the middle lobe was lower than the average CUSUM. According to our learning curve, we recommend nodules in the middle lobe as the first choice for beginners with less than 20 nodules experiences. By utilizing ENB-guided localization for middle lobe lung nodules, beginners can gain proficiency in planning the pathway to the target lesion within ENB, and become familiar with the ENB procedure and personnel cooperation during operation, at last successfully localize pulmonary nodules efficiently. It is particularly advisable to select solid nodules consider that even if ENB-guided localization fails, surgeons can still resect the nodule by tactile exploration. Despite the higher complication rate in the middle lobe (3.8%) compared to the lower lobe (0.9%). However, due to the objectivity of the learning curve, a longer OT does not indicate a longer learning curve, clinical outcome, or complication rate, and OT cannot objectively reflect the learning curve (19). Therefore, for beginners, meanwhile, we found that the number of cases required by the learning curve of the upper lobe was similar to that reported by other researchers (13-16). Due to the large angle of the upper lobular bronchi, especially the apical bronchi, the apical segment bronchi (20) increased the difficulty of ENB-guided localization, increasing OT, and the failure of ECW to enter the apical bronchus, leading to navigation failure. Therefore, it is not recommended that beginners to choose the upper apical segment nodules.

We noted a significant difference in ENB-guided localization among the different pulmonary nodules (P=0.006) in the univariate analysis of OT; OT of the lower lobe was longer. Simultaneously, the learning curve of the lower lobe took a long time and fluctuated widely, and the success rate of the lower lobe localization (95.3%) was lower than that of the upper lobe (97%) and middle lobe (100%). Based on the above results, we consider the following reasons: (I) there are deviation in pulmonary nodules between CT scans and after general anesthesia. CT is traditionally performed with a full inspiratory breath hold, and tidal volume ventilation is used in operations under general anesthesia because of CT-to-body divergence; the upper lobe and lower lobe have different ranges of motion (21), the upper lobe was 1.73 cm and the lower lobe was 2–3 cm. (II) During general anesthesia, the diaphragm is lifted, compressing the lung tissue of the lower lobe and resulting in atelectasis (22,23). Atelectasis makes it difficult for the LG probe to reach the visceral pleura, resulting in an increased OT. To stain the visceral pleura as much as possible, we attempted to achieve this by injecting the stain with a puncture needle or increasing the dose of the stain. However, some PPNs still failed to be stained. In the future, we will investigate how to improve intraoperative atelectasis and reduce the discrepancy between tidal volume ventilation and CT scans by providing adequate positive end-expiratory pressure (PEEP) during general anesthesia (24).

There are a few limitations in this study. First, it was a series of cases from a single center; consequently, it cannot be generalized. Second, this was a retrospective study design, which was subjected to selection bias.

Conclusions

The CUSUM method for analyzing the learning curve was successful in objectively evaluating the mastery of the ENB-guided thoracoscopic pulmonary nodule resection. The learning curve leveled off at the 107th nodule and began to decline after that. Different lobes have different learning curves; the middle lobe is the easiest lobe to learn with ENB and can be used as the first lobe of choice for beginners. The learning curve can objectively evaluate the accuracy of ENB location and help endoscopists identify areas for improvement. Male and current smokers may need a shorter OT but require a longer OT for the distance from localization to the pleura in the lower lobe.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-337/rc

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Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://tlcr.amegroups.com/article/view/10.21037/tlcr-24-337/coif). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). This study was approved by the Ethics Committee of The Second Affiliated Hospital of Air Force Military Medical University (No. K202208-10), and informed consent was obtained from the patients and their families for all studies.

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