

The Learning Curve of the Thoracic Phase in Single-Port Thoracoscopic Esophagectomy for Esophageal Cancer

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Abstract

Objective

Single-port thoracoscopic esophagectomy is an emerging minimally invasive technique that offers potential advantages in reducing surgical trauma and accelerating postoperative recovery. However, its learning curve has not been well characterized. This study aimed to evaluate the learning curve of single-port thoracoscopic esophagectomy and to determine the number of cases required to achieve technical proficiency.

Methods and analysis:

A retrospective analysis was conducted on 220 patients with esophageal squamous cell carcinoma who underwent single-port thoracoscopic esophagectomy between August 2018 and December 2022 at a single center. The cumulative sum (CUSUM) method was employed to assess the learning curve based on operative time. Perioperative outcomes including operative time, intraoperative blood loss, complication rates, and postoperative recovery indicators were compared between different learning phases.

Results

CUSUM analysis revealed an inflection point at the 109th case, dividing the learning process into an initial phase (cases 1-109) and a proficiency phase (cases 110–220). Compared to the initial phase, the thoracic operative time was significantly reduced in the proficiency phase (67.32 ± 12.32 vs. 71.72 ± 12.15 minutes, $P = 0.008$), and intraoperative blood loss was also significantly decreased (96.85 ± 72.39 vs. 125.50 ± 85.50 mL, $P = 0.008$). Although the incidence of major complications declined in the proficiency phase (10.81% vs. 17.59%), the difference did not reach statistical significance (OR = 0.57, 95% CI: 0.26–1.24, $P = 0.154$). Furthermore, patients in the proficiency phase experienced lower postoperative VAS pain scores and shorter hospital stays.

Conclusion

Single-port thoracoscopic esophagectomy has a relatively steep learning curve, with approximately 109 cases required to reach technical proficiency. Once proficiency is achieved, significant improvements in operative efficiency and patient recovery can be observed. These findings have important implications for the training and promotion of single-port thoracoscopic esophagectomy and suggest that this surgery should be performed by surgeons with extensive thoracoscopic experience under expert guidance.

1. Introduction

Esophageal cancer is one of the most common malignancies worldwide (1). Because the majority of patients present with locally advanced disease at diagnosis, multidisciplinary strategies with surgical resection as the cornerstone remain the mainstay of treatment (2). Conventional open thoracotomy is associated with considerable surgical trauma and a high rate of postoperative complications, often leading to delayed recovery. In contrast, the advent of multi-port video-assisted thoracoscopic surgery (VATS) has significantly lowered postoperative morbidity and demonstrated clear advantages in terms of reduced pain, shorter hospital stay, and faster convalescence (3),(4). More recently, single-port VATS esophagectomy an emerging technique in minimally invasive surgery has attracted growing attention. By completing the entire operation through a single incision, this approach further decreases postoperative complications and intercostal nerve injury, thereby expediting patient recovery (5).

The learning curve refers to the progressive improvement in operative metrics such as procedure time and complication rates as the number of cases performed by a surgeon increases (6),(7). Despite the numerous advantages of the single-port approach, the esophagus's complex anatomy, the limited intrathoracic workspace, and the broad operative field make the procedure highly demanding, resulting in a comparatively steep learning curve (8),(9).

To date, studies examining the learning curve for single-port thoracoscopic radical esophagectomy are relatively scarce. Existing evidence suggests that, after accumulating a certain number of thoracoscopic cases, experienced surgeons can markedly reduce operative time, limit intraoperative blood loss, and decrease postoperative complication rates (10),(11). With advances in robotic technology, robot-assisted thoracoscopic esophagectomy is being progressively introduced, which may further reshape the learning curve (12)-(15). Therefore, devising effective strategies to shorten the learning curve, optimize surgical workflow, and lower the procedural entry threshold for surgeons remains a pressing challenge.

In summary, single-port thoracoscopic radical esophagectomy is an emerging minimally invasive technique with considerable clinical promise; however, its learning curve has yet to be fully elucidated. The present study is designed to characterize this curve by examining temporal trends in operative time, intraoperative blood loss, and complication rates across consecutive case cohorts. By quantifying technical maturation and safety at each stage, we aim to generate robust evidence that will facilitate wider adoption of this procedure and inform the development of standardized training programs.

2. Materials and Methods

2.1 Patients

This retrospective study encompassed 220 consecutive patients with esophageal squamous cell carcinoma treated at our center between August 2018 and December 2022. For every case, the thoracic phase of the operation was performed using a single-port thoracoscopic approach. This study was

approved by the Ethics Committee of Fujian Cancer Hospital, and all procedures conformed to the relevant guidelines and regulations. Written informed consent was obtained from all patients.

Inclusion criteria: (1) Age ≥ 18 years, irrespective of sex. (2) Histologically or cytologically confirmed esophageal squamous cell carcinoma. (3) Tumor located in the thoracic segment of the esophagus. (4) No distant metastasis on preoperative staging; clinical stage cT1b-4aN0-2 M0 according to the 8th edition of the American Joint Committee on Cancer (AJCC) staging system. (5) Eastern Cooperative Oncology Group (ECOG) performance status of 0–1.

Exclusion criteria: (1) Presence of any additional primary malignancy other than the index esophageal cancer. (2) Previous exposure to chemotherapy, radiotherapy, immunotherapy, or other antineoplastic treatments for any condition. (3) Evidence of distant metastasis on preoperative evaluation. (4) Inability to tolerate surgery as determined by multidisciplinary assessment.

2.2 Treatment options

Patients received albumin-bound paclitaxel at 260 mg/m² plus cisplatin at 75 mg/m², with or without an immune checkpoint inhibitor including toripalimab (240 mg), tislelizumab (200 mg), sintilimab (200 mg), or pembrolizumab (200 mg). Treatment was administered every 3 weeks as one cycle, for a total of 2–4 cycles.

Toxicities during the neoadjuvant treatment period were closely monitored and assessed according to the Common Terminology Criteria for Adverse Events (CTCAE) version 5.0 issued by the National Cancer Institute. Vital signs, body weight, symptom descriptions, and laboratory test results were recorded weekly to evaluate treatment-related toxicities. Upon completion of neoadjuvant therapy, restaging was performed using contrast-enhanced CT of the neck, chest, and abdomen, or PET-CT when necessary. Surgical resection was scheduled 4–6 weeks after the end of neoadjuvant therapy, depending on the patient's physical condition.

2.3 Surgical Procedures

Under general anesthesia with double-lumen endotracheal intubation, the patient was placed in the left lateral decubitus position (90°). A 3–5 cm incision was made at the right fourth intercostal space between the posterior and mid-axillary lines, serving as both the operative and observation port. The surgeon and the assistant stood on the ventral side of the patient, with the surgeon positioned caudally and the assistant cranially, while the nurse stood on the dorsal side.

Surgical Procedure: (1) Thoracoscopic exploration was performed after establishing the working port. The entire esophageal was carefully examined, especially in cases where imaging or endoscopy suggested a bulky tumor. Special attention was paid to assessing the tumor's relationship with adjacent vital structures to evaluate the feasibility of surgery.

(2) Mobilization of the middle and lower thoracic esophagus: The mediastinal pleura was incised along the inferior border of the azygos vein using an ultrasonic scalpel. The esophagus was dissected bluntly

and sharply downward toward the diaphragmatic hiatus. During posterior dissection beneath the azygos arch and descending aorta, the thoracic duct must be carefully identified and preserved. Enlarged lymph nodes are often found beneath the left inferior pulmonary vein and may adhere tightly to the vein or the contralateral pulmonary ligament. To reduce the risk of vascular injury, these lymph nodes should be dissected after adequate esophageal mobilization and exposure.

(3) Management of the azygos arch: The mediastinal pleura below the arch is incised, and the loose tissue underneath is cleared using an ultrasonic scalpel or dissector. One or two bronchial arteries often run between the esophagus and the arch and can be divided with the ultrasonic scalpel. The esophagus is then transected at a safe distance from the tumor using a linear stapler, while preserving the arch and completing separation of surrounding structures.

(4) Subcarinal and left hilar lymphadenectomy: The mediastinal pleura was incised at the junction between the right intermediate bronchus and the right inferior pulmonary vein. Dissection was performed along the outer membrane of the lymph nodes and bronchial spaces upward. Alternating dissection between the nodes and the adjacent bronchi and pericardium continued until reaching the subcarina. A thick bronchial artery often supplies the subcarinal nodes and can be divided using the ultrasonic scalpel. The left hilar nodes are usually continuous with the subcarinal group and can be exposed by retracting the lymph node capsule, with caution to avoid injury to the left inferior pulmonary vein.

(5) Right recurrent laryngeal nerve lymph node dissection: The mediastinal pleura posterior to the vagus nerve was opened and dissection proceeded cranially toward the subclavian artery. Upon opening the pleura overlying the subclavian artery, the right RLN was identified.

(6) Left recurrent laryngeal nerve lymph node dissection: The assistant retracted the carina and lower trachea downward to expose the region between the lower trachea and the left main bronchus. The 106tbL lymph nodes were excised along the bronchus. The mesentery over the tracheal cartilage rings was incised to expose the left RLN.

2.4 Statistical Analysis

Continuous variables were expressed as mean $\pm$ standard deviation (SD) or median with interquartile range (IQR), and were compared using the Student's t-test or the Wilcoxon rank-sum test, as appropriate. Categorical variables were presented as frequencies (percentages) and compared using the χ^2 test or Fisher's exact test. A P value < 0.05 was considered statistically significant. All statistical analyses were performed using R software.

The cumulative sum (CUSUM) method was employed to evaluate the learning curve for uniportal thoracoscopic esophagectomy in this study. Originally developed for quality control in industrial processes, CUSUM is a sequential analysis technique that has been increasingly adopted in surgical research due to its high sensitivity in detecting subtle and continuous changes in performance.

The operative time of each case was denoted as $X_1, X_2, \dots, X_i$, and the target time (T) was defined as the mean operative time across all cases. The CUSUM value for the i -th case (S_i) was calculated based on the deviation of X_i from T . When the operative time of a case exceeded the target ($X_i > T$), the CUSUM curve ascended; conversely, when $X_i < T$, the curve descended. A CUSUM plot was generated by mapping the sequential case number on the x-axis and the corresponding CUSUM value on the y-axis. This curve visually reflects the cumulative deviation of operative time from the target value and reveals the transitional phases of the learning process. The inflection point of the CUSUM curve is calculated by fitting the curve, marking the transition from the initial learning stage to the proficient mastery stage. Cases prior to this point represent the surgeon's learning period, while subsequent cases demonstrate improved efficiency and technical maturation. Statistical analyses were conducted using R software (version 4.2). $P < 0.05$ was considered statistically significant.

$$S_i = \sum_{j=1}^i (X_j - T)$$

3. Result

3.1 Basic characteristics of patients

Baseline characteristics of the patients are summarized in Table 1. A total of 220 patients were included in this study, comprising 160 males (72.73%) and 60 females (27.27%), with a mean age of 62.45 ± 7.96 years. The majority of patients (199 cases, 90.45%) had an ECOG performance status score of 0. All enrolled patients were diagnosed with squamous cell carcinoma. Among them, 125 patients (56.82%) had tumors located in the middle thoracic esophagus, and 189 patients (85.91%) received neoadjuvant therapy.

Table 1
Patients' characteristics at baseline

Variables	Total (n = 220)
Age, years (Mean $\pm$ SD)	62.45 $\pm$ 7.96
Gender, n(%)	
Females	60 (27.27)
Males	160 (72.73)
Body Mass Index, (Mean $\pm$ SD)	21.79 $\pm$ 2.44
Former smoker, n(%)	68 (30.91)
ECOG, n(%)	
0	199 (90.45)
1	21 (9.55)
Comorbidities, n(%)	
Cardiovascular/Hypertension	28 (12.73)
Diabetes mellitus	10 (4.55)
Pulmonary	25 (11.36)
Neoadjuvant treatment, n(%)	189 (85.91)
Tumor location, n(%)	
Upper	21 (9.54)
Middle	125 (56.82)
Low	74 (33.64)
Histological, n(%)	
Squamous cell carcinoma	220 (100.00)
Clinical T stage, n(%)	
1	57 (25.91)
2	35 (15.91)
3	113 (51.36)
4	15 (6.82)
Clinical N stage, n(%)	
0	53 (24.10)

Variables	Total (n = 220)
1	127 (57.72)
2	33 (15.00)
3	7 (3.18)

3.2 The learning curve of the thoracic phase in single-port thoracoscopic three-field esophagectomy for esophageal cancer

Figure 2.A displays the raw thoracic operation time plotted against the chronological sequence of cases. A fitted linear regression line is superimposed, showing a negative slope, which indicates a gradual reduction in operative time over the course of the series. Despite considerable variability in individual case durations, the overall trend reflects improved efficiency and technical proficiency with experience.

Figure 2.B presents the Cumulative Sum (CUSUM) analysis of operative time. The Y-axis represents the cumulative deviation from the mean operative time, and the X-axis represents case sequence. This inflection point (case 109) clearly delineated two distinct phases in the learning process: Initial learning phase (cases 1–109): During this phase, the CUSUM curve showed a continuous upward trend, indicating that operative times were generally above the average level. This reflects the surgeon's ongoing learning and adaptation to the procedure. The steep ascent in the early part of the curve suggests a relatively steep learning curve, requiring a substantial number of cases to master the key technical aspects. Proficiency phase (cases 110–220): In this phase, the CUSUM curve began to decline, indicating that operative times were generally below the average, and surgical efficiency had markedly improved. The reduced fluctuation of the curve suggests increasing consistency and stability in operative times, marking the surgeon's transition into a phase of technical proficiency.

3.3 Perioperative Outcomes

Table 2. summarizes the main perioperative outcomes between the two phases. Compared with the initial learning phase (Phase 1, n = 109), patients in the proficient phase (Phase 2, n = 111) had significantly shorter thoracic operative times (67.32 ± 12.32 vs. 71.72 ± 12.15 minutes, $P = 0.008$) and less intraoperative blood loss (96.85 ± 72.39 vs. 125.50 ± 85.50 mL, $P = 0.008$). No cases in either group required conversion to thoracotomy. There were no statistically significant differences between the two phases in terms of postoperative drainage volume (348.10 ± 145.38 vs. 345.53 ± 135.45 mL, $P = 0.892$), gastric fluid drainage volume (887.21 ± 211.05 vs. 952.25 ± 386.26 mL, $P = 0.124$), duration of chest tube placement (3.53 ± 1.49 vs. 3.83 ± 1.89 days, $P = 0.187$), complication rate (10.81% vs. 17.59%, $P = 0.150$), Clavien–Dindo complication grade distribution, VAS pain scores, or the number of lymph nodes dissected (18.13 ± 6.33 vs. 17.29 ± 5.79 , $P = 0.310$). However, the median postoperative hospital stay was significantly shorter in the proficient phase group (7.0 [7.0–8.0] vs. 8.0 [7.0–9.0] days, $P < 0.001$).

Table 2
Intraoperative and postoperative outcomes

Variables	Phase 1 (n = 109)	Phase 2 (n = 111)	<i>P</i>
Thoracic phase time (minutes), Mean ± SD	71.72 ± 12.15	67.32 ± 12.32	0.008
Intraoperative blood loss (ml), Mean ± SD	125.50 ± 85.50	96.85 ± 72.39	0.008
Conversion to thoracotomy	0(0.00)	0(0.00)	-
Postoperative drainage volume (ml), Mean ± SD	348.10 ± 145.38	345.53 ± 135.45	0.892
Postoperative gastric juice volume (ml), Mean ± SD	952.25 ± 386.26	887.21 ± 211.05	0.124
Duration of drainage tube placement, Mean ± SD	3.83 ± 1.89	3.53 ± 1.49	0.187
Length of hospital stay (d), IQR	8.00(7.00,9.00)	7.00(7.00,8.00)	<0.001
Complication, n(%)	19 (17.59)	12 (10.81)	0.150
Anastomotic leak, n(%)	6 (5.50)	4 (3.60)	0.724
Pneumonia, n(%)	8 (7.34)	2 (1.80)	0.099
Recurrent laryngeal nerve injury, n(%)	2 (1.83)	1 (0.90)	0.987
Arrhythmia, n(%)	1 (0.92)	2 (1.80)	1.000
Chylothorax, n(%)	2 (1.83)	3 (2.70)	1.000
Clavien-Dindo, n(%)			0.878
1	3 (15.79)	3 (25.00)	
2	14 (73.68)	9 (75.00)	
3a	1 (5.26)	0 (0.00)	
3b	1 (5.26)	0 (0.00)	
4a	0 (0.00)	0 (0.00)	
4b	0 (0.00)	0 (0.00)	
5	0 (0.00)	0 (0.00)	
VAS score on postoperative day 1, n(%)			0.144
1	0 (0.00)	4 (3.60)	
2	5 (4.59)	9 (8.11)	
3	19 (17.43)	27 (24.32)	
4	36 (33.03)	32 (28.83)	

Variables	Phase 1 (n = 109)	Phase 2 (n = 111)	<i>P</i>
5	29 (26.61)	28 (25.23)	
6	16 (14.68)	8 (7.21)	
7	3 (2.75)	1 (0.90)	
8	1 (0.92)	2 (1.80)	
VAS score at 1 week postoperatively, n(%)			0.543
0	0 (0.00)	2 (1.80)	
1	39 (35.78)	37 (33.33)	
2	31 (28.44)	38 (34.23)	
3	25 (22.94)	22 (19.82)	
4	14 (12.84)	12 (10.81)	
Lymph node harvest, Mean ± SD	17.29 ± 5.79	18.13 ± 6.33	0.310
Tumor grade, n(%)			0.010
G1	42 (38.53)	45 (40.54)	
G2	49 (44.95)	52 (46.85)	
G3	9 (8.26)	14 (12.61)	
Gx	9 (8.26)	0 (0.00)	
Pathological T stage, n(%)			0.631
0	0 (0.00)	2 (1.80)	
1	21 (19.27)	24 (21.62)	
2	19 (17.43)	20 (18.02)	
3	62 (56.88)	60 (54.05)	
4	7 (6.42)	5 (4.50)	
Pathological N stage, n(%)			0.726
0	60 (55.05)	57 (51.35)	
1	25 (22.94)	23 (20.72)	
2	19 (17.43)	22 (19.82)	
3	5 (4.59)	8 (7.21)	

Variables	Phase 1 (n = 109)	Phase 2 (n = 111)	<i>P</i>
4	0 (0.00)	1 (0.90)	
30-day readmission, n(%)	1 (0.92)	1 (0.90)	1.000
90-day mortality, n(%)	0(0.00)	0(0.00)	-

3.4 Univariate Logistic Regression Analysis of Postoperative Complicati

To investigate the association between different phases of the learning curve and the occurrence of major postoperative complications, univariate logistic regression analysis was performed. Based on the results of the CUSUM analysis, patients were divided into Phase 1 (the first 109 cases) and Phase 2 (case 110 onward). The incidence of major postoperative complications was 17.6% (19/108) in Phase 1 and 10.8% (12/111) in Phase 2. Although the difference did not reach statistical significance (OR = 0.57, 95% CI: 0.26–1.24, $P = 0.154$), the odds ratio suggests a decreasing trend in complication risk with increased surgical experience. Additionally, other potentially relevant variables including age, sex, body mass index, ECOG performance status, tumor location, intraoperative blood loss, extent of lymph node dissection, clinical T/N stage, and receipt of neoadjuvant therapy were analyzed using univariate logistic regression. None of these variables showed a statistically significant association with postoperative complications ($P > 0.05$). These findings indicate that although the learning phase was not statistically associated with complication rates in the univariate model, the observed reduction in complications during Phase 2 suggests a potential role of surgical experience in mitigating risk.

Table 3
Univariate Logistic Regression Analysis of Postoperative Complications

Variables	No major complication (n = 188)	Major complication (n = 31)	<i>P</i>	OR (95%CI)
Age				
<65	121 (64.36)	16 (51.61)	0.177	1.69 (0.79 ~ 3.64)
≥65	67 (35.64)	15 (48.39)		
Gender				
Females	54 (28.72)	6 (19.35)	0.283	1.68 (0.65 ~ 4.32)
Males	134 (71.28)	25 (80.65)		
BMI				
<18.5	17 (9.04)	4 (12.90)	0.461	0.64 (0.20 ~ 2.08)
18.5–25	152 (80.85)	23 (74.19)		
>25	19 (10.11)	4 (12.90)	0.887	0.89 (0.19 ~ 4.14)
ECOG				
0	170 (90.43)	28 (90.32)	0.986	1.01 (0.28 ~ 3.66)
1	18 (9.57)	3 (9.68)		
Tumor location				
Upper	18 (9.57)	3 (9.68)	0.813	0.84 (0.21 ~ 3.45)
Middle	64 (34.04)	9 (29.03)		
Low	106 (56.38)	19 (61.29)	0.914	1.08 (0.29 ~ 4.01)
Intraoperative blood loss				
<100	37 (19.68)	4 (12.90)	0.374	1.65 (0.55 ~ 5.02)
≥100	151 (80.32)	27 (87.10)		
Group				
Phase 1	89 (47.34)	19 (61.29)		

Variables	No major complication (n = 188)	Major complication (n = 31)	<i>P</i>	OR (95%CI)
Age				
Phase 2	99 (52.66)	12 (38.71)	0.154	0.57 (0.26 ~ 1.24)
Lymph node harvest				
<18	86 (45.74)	19 (61.29)		
≥18	102 (54.26)	12 (38.71)	0.958	0.98 (0.46 ~ 2.10)
Clinical T stage				
1	48 (25.53)	9 (29.03)		
2	31 (16.49)	4 (12.90)	0.561	0.69 (0.19 ~ 2.43)
3	98 (52.13)	15 (48.39)	0.657	0.82 (0.33 ~ 2.00)
4	11 (5.85)	3 (9.68)	0.615	1.45 (0.34 ~ 6.27)
Clinical N stage				
0	46 (24.47)	7 (22.58)		
1	108 (57.45)	18 (58.06)	0.849	1.10 (0.43 ~ 2.80)
2	28 (14.89)	5 (16.13)	0.800	1.17 (0.34 ~ 4.06)
3	6 (3.19)	1 (3.23)	0.937	1.10 (0.11 ~ 10.51)
Neoadjuvant treatment				
No	162 (86.17)	27 (87.10)		
Yes	26 (13.83)	4 (12.90)	0.889	0.92 (0.30 ~ 2.85)

4. Discussion

This study investigated the learning curve characteristics of single-port thoracoscopic esophagectomy, analyzing the impact of surgeon proficiency on operation time, intraoperative blood loss, and complication rates. The study included 220 consecutive patients who underwent single-port

thoracoscopic esophagectomy, systematically evaluating trends throughout the learning process through a retrospective cohort analysis spanning four years (August 2018 to December 2022). Using the CUSUM method, we identified that the surgeon reached an inflection point in the learning curve after completing 109 procedures, entering the proficiency stage, demonstrated by significantly reduced thoracic operation time (67.32 ± 12.32 vs. 71.72 ± 12.15 minutes, $P = 0.008$) and decreased intraoperative blood loss (96.85 ± 72.39 vs. 125.50 ± 85.50 mL, $P = 0.008$). Although postoperative complication rates showed a declining trend (10.81% vs. 17.59%), the difference did not reach statistical significance (OR = 0.57, 95% CI: 0.26–1.24, $P = 0.154$), suggesting that single-port thoracoscopic esophagectomy is a complex procedure with a steep learning curve, but surgical efficiency can be significantly improved through systematic training.

Single-port thoracoscopic esophagectomy for esophageal cancer is a technically demanding procedure with a relatively steep learning curve. Compared to existing literature, we found that the number of cases required to achieve proficiency in this technique is higher than that for some other minimally invasive esophagectomy (MIE) methods. In a study by Wang et al. on single-port thoracoscopic modified McKeown esophagectomy, approximately 50 cases were needed to reach a stable level of surgical proficiency, with significantly reduced operative time and intraoperative blood loss in the proficiency phase compared to the initial phase findings that differ somewhat from ours (16). Similarly, Nachira et al. reported a gradual reduction in operative time from 196.1 ± 33.5 minutes to 156.2 ± 27.3 minutes ($P < 0.001$) with increasing experience in single-port esophagectomy (17). Compared to these studies, our results suggest that single-port thoracoscopic radical esophagectomy may require a longer learning period, which could be attributed to the technical complexity of the procedure, the surgeon's background, and differences in specific techniques employed across studies.

When compared with robot-assisted minimally invasive esophagectomy (RAMIE), the learning curve for single-port thoracoscopic radical esophagectomy appears even steeper. Van der Sluis et al. reported an initial learning phase of 70 cases and a complete learning curve of approximately 120 cases for RAMIE based on an analysis of 312 patients (18). Yang et al. similarly identified an initial learning phase of 40 cases and a proficiency phase after 175 cases (19). These differences may be due to the advantages of robotic systems, such as three-dimensional visualization and articulated instruments, which facilitate more precise surgical maneuvers and reduce the technical threshold.

In our study, with increasing surgical experience, perioperative Outcomes showed significant improvement. In the second phase (case 110 and beyond), thoracic operative time and intraoperative blood loss were both significantly reduced compared to the initial phase, which aligns with findings from other MIE studies (20)–(22). For example, Tapias and Morse suggested that 35 to 40 cases were needed to achieve proficiency in minimally invasive Ivor Lewis esophagectomy (20), while Guo et al. reported that technical competency in thoracoscopic-assisted esophagectomy could be reached after 26 cases (21). However, due to the restricted operative field and instrument interference inherent to single-port techniques, a longer learning process may be required, as reflected in our findings.

Although operative outcomes differed between the two phases, there was no statistically significant difference in the incidence of major postoperative complications (17.6% in Phase 1 vs. 10.8% in Phase 2, $P = 0.154$). Nevertheless, the trend toward decreased complications (OR = 0.57, 95% CI: 0.26–1.24) suggests that surgical experience may contribute to improved patient safety. This observation is consistent with findings from studies on other MIE techniques (23),(24). For instance, Sun et al. demonstrated a significant reduction in major complications with increased experience in robot-assisted McKeown esophagectomy (23), and similar results were reported by Zhang et al (24).

Moreover, our study revealed a correlation between the learning curve phases and other clinical indicators such as postoperative pain and hospital stay. Patients in Phase 2 reported lower VAS scores on both postoperative day 1 and at 1 week, and experienced shorter hospitalizations, suggesting that improvements in surgical proficiency also translated into enhanced postoperative recovery. These findings are consistent with previous reports highlighting the advantages of single-port thoracoscopic surgery in terms of reduced trauma and faster recovery (25),(26).

This study has several limitations. First, it was a retrospective, single-center study based on the experience of a single surgeon, which may introduce selection bias. Second, the learning curve was primarily assessed based on operative time, without incorporating other metrics of surgical quality such as the number of lymph nodes dissected or R0 resection rate. Third, while we observed a downward trend in postoperative complications, the difference was not statistically significant, possibly due to the limited sample size. Lastly, long-term follow-up data were not available, preventing evaluation of the impact of the learning curve on long-term oncologic outcomes.

Our study provides a systematic evaluation of the learning curve for single-port thoracoscopic radical esophagectomy and may serve as a reference for the dissemination and training of this technique. Compared with RAMIE and multiport thoracoscopic esophagectomy, our findings suggest that single-port procedures require a longer learning curve. However, once the initial learning phase is overcome, single-port thoracoscopy offers favorable surgical outcomes and patient benefits. Therefore, we recommend that this procedure be performed by surgeons with adequate thoracoscopic experience and under expert supervision during the learning phase to ensure safety and efficacy.

Declarations

Data availability

Due to privacy concerns, the data is not publicly available, but can be obtained from the corresponding author upon reasonable request.

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(VI) Manuscript writing: All authors

(VII) Final approval of manuscript: All authors

Ethics declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Fujian Cancer Hospital (SQ2025-101) and study was conducted under the guidance of the Declaration of Helsinki. All participants signed a written informed consent form.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Figures

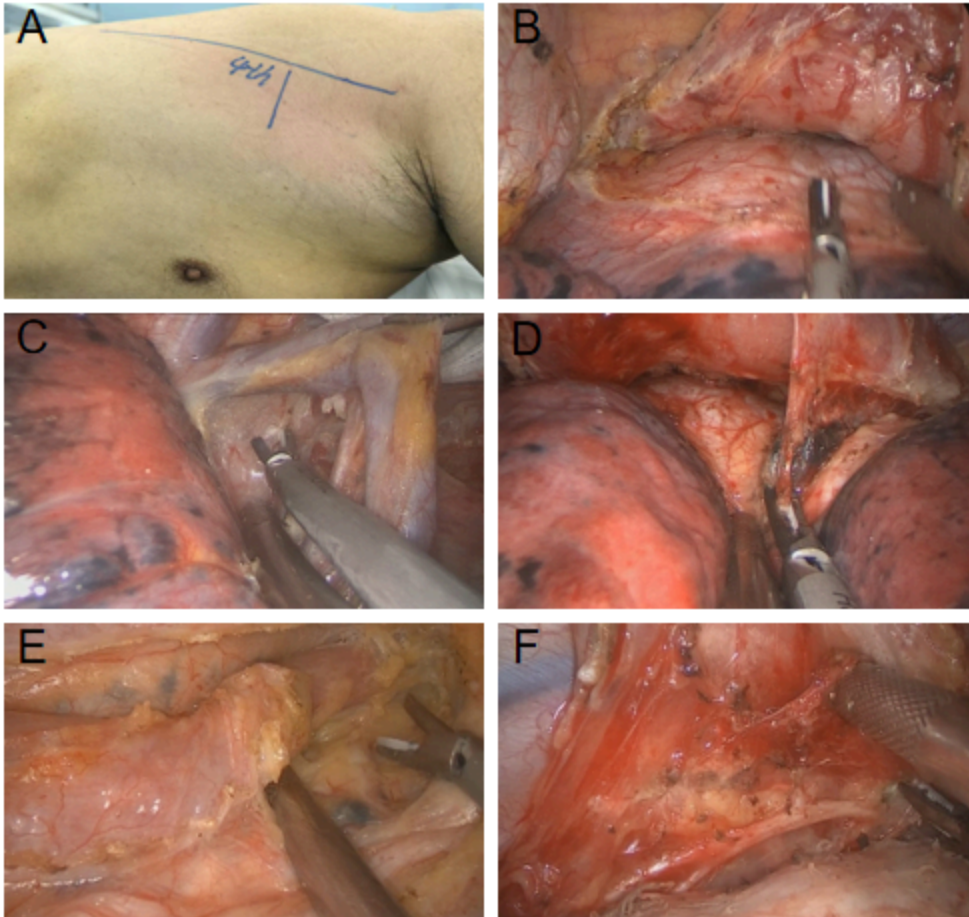


Figure 1

(A) Patient position and the working port. (B) Mobilization of the middle and lower thoracic esophagus. (C) Management of the azygos arch. (D) Subcarinal and left hilar lymphadenectomy. (E) Right recurrent laryngeal nerve lymph node dissection. (F) Left recurrent laryngeal nerve lymph node dissection.

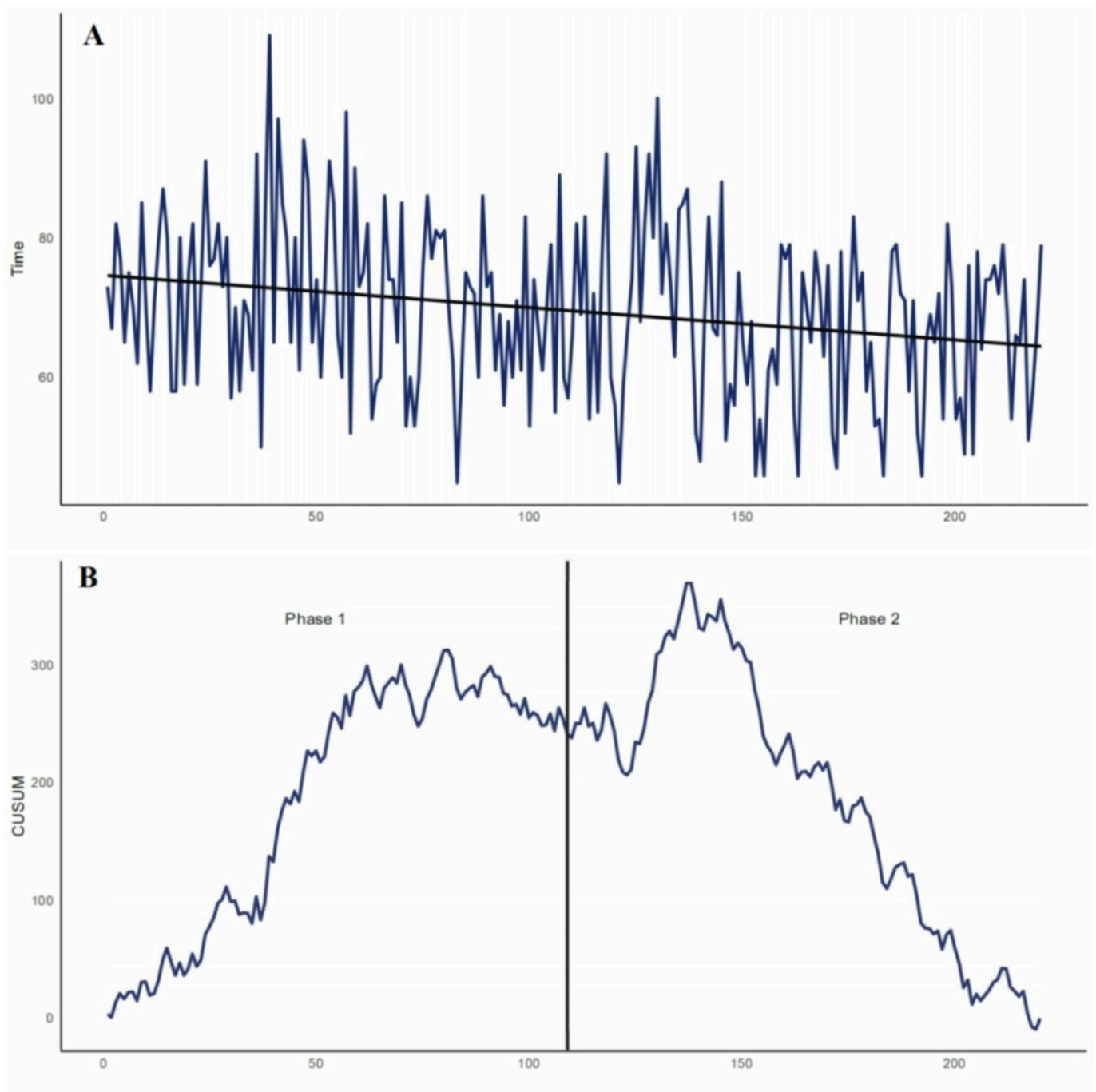


Figure 2

(A) The raw thoracic operation time plotted against the chronological sequence of cases. (B) According to the CUSUM curve of the 220 patients included, there were two phases: phase 1 (cases 1–109), phase 2 (cases 110–220), with an inflection point at cases 109.