



# From McKeown to Ivor Lewis, the learning curve for thoracic lymphadenectomy over the first 100 robotic esophagectomy cases: a retrospective study

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**Background:** Lymphadenectomy is an essential but challenging part of the surgical treatment for esophageal cancer. However, the previously reported learning curve for robotic esophagectomy primarily focused on only one surgical approach (McKeown or Ivor Lewis). However, both approaches must be mastered by a mature robotic surgical team to deal with different clinical conditions and satisfy patients' needs. This study aimed to show how an experienced esophageal surgical team became proficient in both McKeown and Ivor Lewis robotic esophagectomy.

**Methods:** A retrospective review of the first 100 cases of robot-assisted minimally invasive esophagectomy (RAMIE) by a single surgical team was performed. The cumulative sum (CUSUM) analysis was used to distinguish the change point during the learning course. A subgroup analysis was performed according to a surgical approach (McKeown or Ivor Lewis) to determine the effect of experience from one surgical approach on learning the other RAMIE technique.

**Results:** According to the tendency of the CUSUM plot, the learning curve was divided into four phases. The subgroup analysis indicated the decline of the CUSUM plot in the 3rd phase originated from the start of the Ivor Lewis approach. The attending surgeon took 23 cases to achieve a significant improvement in the number of harvested thoracic lymph nodes using the McKeown approach. Regardless of the acquired experience of McKeown RAMIE, it took another 18 cases for the surgical team to achieve significant improvement in harvesting thoracic lymph nodes using the Ivor Lewis approach.

**Conclusions:** Twenty-three cases were needed for an experienced surgical team to improve thoracic lymphadenectomy results using McKeown RAMIE. There was another learning phase during the transition from McKeown to Ivor Lewis esophagectomy. Importantly, the acquired experience from performing McKeown RAMIE could shorten how long it takes to learn Ivor Lewis RAMIE.

**Keywords:** Esophageal cancer; lymphadenectomy; robotic surgery; learning curve

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## Introduction

Esophageal cancer is the 6<sup>th</sup> leading cause of cancer-related death worldwide, and surgery is the best choice for patients with resectable disease (1,2). In addition to surgical resection of the tumor, lymphadenectomy is also a crucial part of a successful surgery (3,4). A thorough lymphadenectomy ensures removal of potentially involved lymph nodes and guarantees maximal clearance of the tumor cell (5). Both the number of involved lymph nodes and the number of total harvested lymph nodes are independent predictors of postsurgical survival (6,7). Therefore, special attention should be paid to the quality of lymphadenectomy. According to the 8<sup>th</sup> edition of the American Joint Committee on Cancer (AJCC) staging criteria, there are 15 thoracic lymph node stations and five abdominal lymph node stations potentially involved in esophageal cancer (8). The National Comprehensive Cancer Network (NCCN) esophageal cancer treatment guidelines recommend that at least 15 lymph nodes be submitted for pathological evaluation to guarantee the accuracy of nodal staging (1).

Considering the importance of harvesting lymph nodes, the learning curve for lymphadenectomy in robotic esophageal surgery has drawn the interest of thoracic surgeons, and a few studies on this topic have been published (9,10). However, thoracic lymphadenectomy, which is the most technically challenging part and involves 15 lymph node stations, has not yet been independently studied. This study aimed to display the learning curve for thoracic lymphadenectomy over the first 100 robot-assisted minimally invasive esophagectomy (RAMIE) cases according to the number of harvested thoracic lymph nodes. A subgroup analysis according to surgical approach (McKeown or Ivor Lewis) was also performed to determine the effect of learning one surgical approach on learning the other RAMIE technique. We present the following article in accordance with the MDAR and STROBE reporting checklist (available at <http://dx.doi.org/10.21037/jtd-20-2862>).

## Methods

This study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The Ethics Committee of West China Hospital of Sichuan University approved this study (20190402). Informed consent to undergo robotic surgery without receiving financial support

from the national health insurance system was obtained from all patients.

A retrospective review of the first 100 RAMIE cases by a single surgical team in West China Hospital was performed. The surgical team is also experienced in open esophagectomy and conventional thoracoscopic minimal invasive esophagectomy (CMIE). The team started RAMIE in 2016. In the beginning, only the McKeown approach was adopted. Then, based on the acquired experience in the McKeown approach, the surgical team expanded the robotic surgery to the Ivor Lewis technique. The detailed surgical techniques of the two approaches have been described previously (11,12). Cases that were converted to open surgery during RAMIE were excluded from the first 100 cases. CMIE cases performed by the surgical team during the same period was also collected as the control group to monitor surgical quality.

### *Baseline data collection*

Baseline patient data, including age, gender, body mass index (BMI), preoperative comorbidities, tumor location, date of surgery, and surgical approach, were collected from the electronic medical records system. Postoperative pathologic reports were exported from the electronic pathologic report system. Malignancies were staged according to the eighth edition of the AJCC staging criteria for esophageal cancer (8).

### *Number of harvested lymph nodes*

In this study, the relevant lymph nodes were divided into two groups: thoracic lymph nodes and abdominal lymph nodes. Although there have been some changes in the classifications of lymph node stations from the 7<sup>th</sup> edition to 8<sup>th</sup> edition of the AJCC staging criteria, these changes have no impact on thoracic and abdominal lymph node classifications (8,13). For example, the 3P station in the 7<sup>th</sup> edition was renamed as the 8U station in the 8<sup>th</sup> edition. However, in both the 7<sup>th</sup> and 8<sup>th</sup> editions, it belongs to the thoracic lymph nodes. Nonetheless, the pathologic reports of some early cases in this study were based on the 7<sup>th</sup> edition. In summary, the thoracic lymph stations included 2L, 2R, 8U, 4L, 4R, 5, 6, 7, 8M, 8Lo, 9L, 9R, 10L, 10R, 15<sup>th</sup> stations, and the 3P, 8L, and 9<sup>th</sup> stations in the 7<sup>th</sup> edition. The abdominal lymph node stations included the 16<sup>th</sup>, 17<sup>th</sup>, 18<sup>th</sup>, 19<sup>th</sup>, and 20<sup>th</sup> lymph node stations.

**Table 1** The baseline characteristics of the first 100 patients who underwent robot-assisted minimally invasive esophagectomy

Variables	N=100
Age (year old)	61.89±7.71
Gender	
Male	84 (84%)
Female	16 (16%)
BMI (kg/m <sup>2</sup> )	23.10±3.61
Diabetes	5 (5%)
Hypertension	26 (26%)
Tumor location	
Upper thorax	13 (13%)
Middle thorax	50 (50%)
Lower thorax	37 (37%)
Histology	
Squamous cell carcinoma	88
Adenocarcinoma	6
Other	6
Pathologic T stage	
Tis	1
T1	20
T2	24
T3	49
T4a	6
Pathologic N stage	
N0	52
N1	26
N2	15
N3	7
TNM stage	
0	1
I	14
II	42
III	34
IVa	9
Surgical approach	
McKeown	69
Ivor Lewis	31
Number of RCLN-LN	2.19 ±2.31
Number of Thoracic LN	9.97±4.78
Number of Abdomen LN	10.66±6.87
Number of Total LN	20.63±8.30

BMI, body mass index; LN, lymph node; RLN-LN, recurrent laryngeal nerve lymph node.

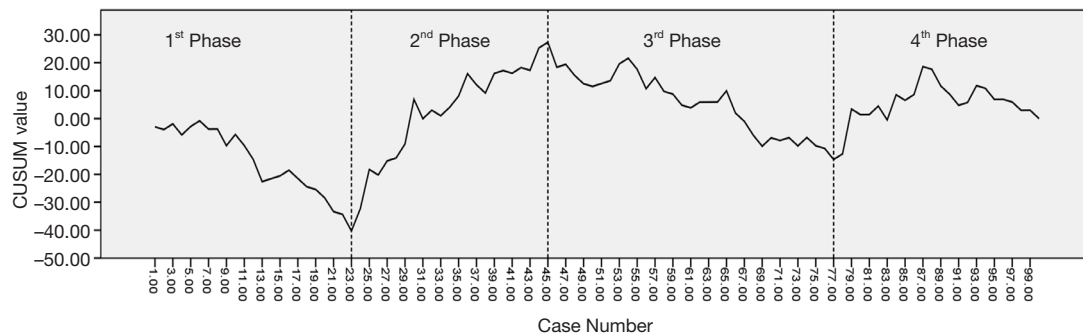
### Statistical analysis

The cumulative sum (CUSUM) analysis is one of the most well-known monitoring methods for sequential data (14). CUSUM values were calculated in Excel 2010 (Microsoft, Redmond, WA, USA) according to the following formula:  $CUSUM = \sum_i^{100} (xi - u)$ , where  $xi$  stands for the true value of the  $i^{\text{th}}$  case and  $u$  stands for the mean value of the examined variable. Changes in the CUSUM value reflect the running total of data deviation from the mean value of the group. If the actual measured value is above the group's mean value, then CUSUM values will increase. Thus, we can observe the changing tendency of sequential data by the changing CUSUM value. Points with the largest peaks in the CUSUM curve were identified as the change points of the learning curve. The significance of the change points was further tested by comparing the true value before and after the point. Subgroup analysis was performed according to surgical approach (McKeown or Ivor Lewis) to see the individual learning curves of the two surgical approaches.

SPSS 22.0 software (IBM, Armonk, NY, USA) was used for all statistical analyses and to draw the CUSUM learning curves. Student's *t*-test or one-way ANOVA were applied to compare the integrated parameters, while the Chi-squared test or Fisher's exact test were applied to dichotomous data. P values <0.05 were considered statistically significant.

### Results

The surgical team accomplished their 100<sup>th</sup> case of robotic esophagectomy in February 2018. Two cases were converted to open surgery during the period, one due to severe pleural adhesion and another due to large mixed lymph nodes invading the celiac trunk. Both were excluded from the first 100 cases. *Table 1* shows baseline characteristics of the first 100 patients who underwent RAMIE. The mean age of the patients was 61.89-years-old, with a mean BMI of 23.10 kg/m<sup>2</sup>. The number of male patients was much greater than the number of female patients (86 versus 14, respectively). Twenty-six patients had a history of hypertension, while five had a history of diabetes. Squamous cell carcinoma (88%) was the most common histologic type. Fifty patients had a middle thoracic tumor, 37 had a lower thoracic tumor, and the remaining 13 had tumors in the upper thorax. Regarding surgical approach, the McKeown approach was adopted in 69 cases, while the Ivor Lewis approach was used in 31. The mean numbers of harvested recurrent laryngeal nerve lymph nodes, thoracic lymph



**Figure 1** The CUSUM plot of the number of harvested thoracic lymph nodes in the first 100 cases of robot-assisted minimally invasive esophagectomy from a single surgical team. By visual assessment on the CUSUM plot, the learning curve was divided into 4 phases by three turning points (the 23<sup>rd</sup> case, the 45<sup>th</sup> case, the 77<sup>th</sup> case), after which the tendency of the CUSUM plot changed. The first phase consisted of the first 23 cases. In this phase, the CUSUM plot trended downward, which meant the number of harvested lymph nodes in most cases was beneath the mean value of the 100 cases. After the 23<sup>rd</sup> case, the CUSUM plot trended to rise up and reached a peak when it came to the 45<sup>th</sup> case. So the 24<sup>th</sup> to 45<sup>th</sup> made the second phase. Then, another decline occurred between the 46<sup>th</sup> to 77<sup>th</sup> cases. It was the 3<sup>rd</sup> phase. After the 3<sup>rd</sup> phase, the CUSUM value wavered around zero, and the CUSUM plot becomes steady. It made the fourth phase. CUSUM, cumulative sum.

nodes, and abdominal lymph nodes were 2.19, 9.97, and 10.66, respectively. Lymph node metastasis was detected in 48 patients.

#### *The learning curve for lymphadenectomy in the first 100 robotic esophagectomies*

Visual assessment of the CUSUM plot of the first 100 robotic esophagectomies (*Figure 1*) showed three turning points, after which the trend of the CUSUM plot changed. These three turning points divided the learning curve for thoracic lymphadenectomy into four phases. The first phase consisted of the first 23 cases. In this phase, the CUSUM plot trended downward, which meant the number of harvested lymph nodes in most cases was beneath the mean value of the 100 cases. After the 23<sup>rd</sup> case, the CUSUM plot had an increasing trend that peaked by the 45<sup>th</sup> case. So the 24<sup>th</sup> to 45<sup>th</sup> cases comprised the second phase. Then, another decline occurred between the 46<sup>th</sup> to 77<sup>th</sup> cases, which was the 3<sup>rd</sup> phase. After the 3<sup>rd</sup> phase, the CUSUM value wavered around zero, and the CUSUM plot became steady. This was the fourth phase.

The comparison of patients' baseline characteristics and the number of harvested lymph nodes among the four phases are shown in *Table 2*. The mean number of harvested abdominal lymph nodes ranged from 10.06 to 11.35, and it was comparable among the four phases. However, a statistically significant difference was detected in the number of harvested thoracic lymph nodes. The mean

number of harvested thoracic lymph nodes in the 2<sup>nd</sup> phase was 13.05 and was 10.61 in the 4<sup>th</sup> phase. On the contrary, the 1<sup>st</sup> and 3<sup>rd</sup> phases had much smaller mean numbers of harvested thoracic lymph nodes, 8.22 and 8.66, respectively. Due to the steady number of harvested abdominal lymph nodes, the differences among the four phases in the total number of harvested lymph nodes was consistent with the thoracic lymph nodes. The baseline characteristics, including age, gender, BMI, comorbidities, tumor location, and disease stage, were comparable among the four phases. However, the four phases showed significant differences in the surgical approaches. All cases in the first phase underwent the McKeown approach. In the second phase, the Ivor Lewis approach was applied for the first time. But only three patients underwent the new approach. However, the number of Ivor Lewis cases was almost equal to those that underwent the McKeown approach in the third phase, and it exceeded the McKeown approach in the fourth phase.

#### *Lymphadenectomy quality in the four learning phases*

During the same period, the surgical team performed 49 CMIE procedures in addition to the 100 RAMIE cases (*Table S1*). The mean number of total harvested lymph nodes was 17.86 in the 49 patients who underwent CMIE. More lymph nodes were harvested from all four RAMIE learning phases than CMIE. Moreover, the difference between the 2<sup>nd</sup> and 4<sup>th</sup> phases was statistically significant. The number of harvested recurrent laryngeal nerve lymph

**Table 2** Comparison of patients' characteristics and the number of harvested lymph nodes among the four learning phases

Characteristics	Phase 1 (1 <sup>st</sup> -23 <sup>th</sup> )	Phase 2 (24 <sup>th</sup> -45 <sup>th</sup> )	Phase 3 (46 <sup>th</sup> -77 <sup>th</sup> )	Phase 4 (78 <sup>th</sup> -100 <sup>th</sup> )	P value
Age	62.17±7.08	60.09±6.42	63.09±8.74	61.65±8.03	0.572
BMI (kg/m <sup>2</sup> )	23.19±2.90	22.80±2.53	22.88±4.81	23.60±3.32	0.872
Female/male	4/19	3/19	6/26	3/20	0.929
Diabetes	1 (4.3%)	1 (4.5%)	2 (6.3%)	1 (4.3%)	0.984
Hypertension	6 (26.1%)	5 (22.7%)	11 (34.4%)	4 (17.4%)	0.537
Tumor location					0.101
Upper	5 (21.7%)	2 (9.1%)	6 (18.8%)	0 (0.0%)	
Middle and lower	18 (78.3%)	20 (90.9%)	28 (81.3%)	23 (100.0%)	
Surgical approach					0.000
Ivor Lewis	0 (0.0%)	3 (13.6%)	14 (43.8%)	14 (60.9%)	
McKeown	23 (100%)	19 (86.4%)	18 (56.3%)	9 (39.1%)	
Histology					0.841
SCC	21 (91.3%)	20 (90.9%)	27 (84.4%)	20 (87.0%)	
Other	2 (8.7%)	2 (9.1%)	5 (15.6%)	3 (13.0%)	
RLN-LNs	2.00±2.15	2.77±2.22	1.81±2.18	2.22±2.70	0.470
Thoracic LNs	8.22±3.24	13.05±5.64	8.66±3.61	10.61±5.28	0.001
Abdomen LNs	10.61±8.34	10.86±6.24	10.06±6.83	11.35±6.23	0.923
Total LN	18.83±9.13	23.91±7.10	18.72±8.25	21.96±7.85	0.076
T stage					0.608
T0-T2	12 (52.2%)	9 (40.9%)	12 (37.5%)	12 (52.2%)	
T3-T4a	11 (47.8%)	13 (59.1%)	20 (62.5%)	11 (47.8%)	
N stage					0.760
N0-N1	19 (82.6%)	18 (81.8%)	23 (71.9%)	18 (78.3%)	
N2-N3	4 (17.4%)	4 (18.2%)	9 (28.1%)	5 (21.7%)	
TNM Stage					0.583
0-II	12 (52.2%)	12 (54.5%)	17 (53.1%)	16 (70.0%)	
III-IVa	11 (47.8%)	10 (45.5%)	15 (46.9%)	7 (30.0%)	

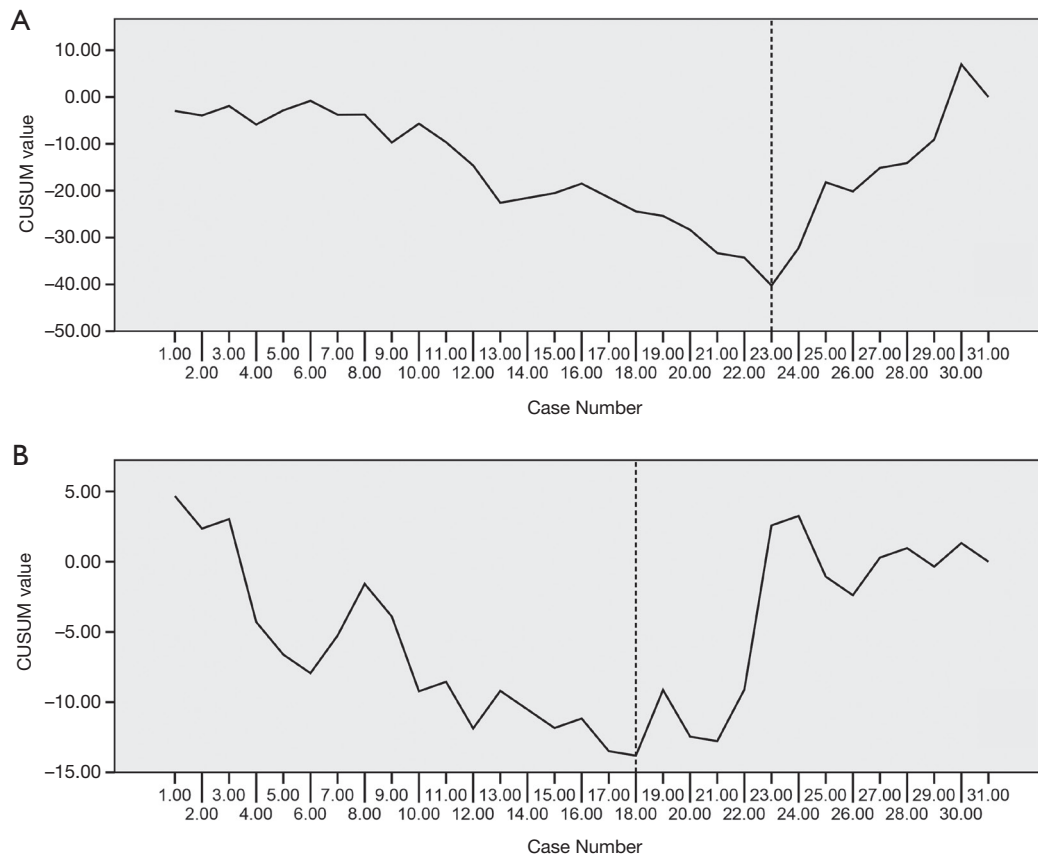
BMI, body mass index; SCC, squamous cell carcinoma; LN, lymph node; RLN-LN, recurrent laryngeal nerve lymph node.

nodes was comparable between CMIE and the four RAMIE learning phases. Therefore, the lymphadenectomy quality of RAMIE was satisfactory.

#### *Lymphadenectomy learning curves according to surgical approach*

A subgroup analysis was performed according to surgical

approach to determine if the change in surgical approach led to the decline in the CUSUM plot in the 3<sup>rd</sup> phase. Among the 32 cases in the 3<sup>rd</sup> phase, 14 underwent the Ivor Lewis approach, while the remaining 18 cases adopted the McKeown approach. The mean numbers of harvested lymph nodes were 7.14 and 9.83 in the Ivor Lewis and McKeown approaches, respectively, which was a statistically significant difference (P=0.034). So the decrease in the



**Figure 2** The CUSUM plot of the number of harvested thoracic lymph nodes in ro-bot-assisted McKeown and Ivor Lewis esophagectomy separately. (A) The CUSUM plot of the number of harvested thoracic lymph nodes in the first 31 cases of robot-assisted McKeown esophagectomy. The tendency of the CUSUM plot changed from downward to upward in the 23rd case. It indicated that it took 23 cases for the surgeons to accomplish the initial exploration of the harvest of the thoracic lymph nodes in the McKeown approach. (B) The CUSUM plot of the number of harvested thoracic lymph nodes in the first 31 cases of robot-assisted Ivor Lewis esophagectomy. The CUSUM plot tended to downward at the beginning, and it reached the lowest point in the 18th case. After that, the CUSUM plot started ascending. It indicated that on the basis of the robot-assisted McKeown lymphadenectomy, the exploration of the thoracic lymphadenectomy in the Ivor Lewis approach took another 18 cases. CUSUM, cumulative sum.

CUSUM learning curve in the 3<sup>rd</sup> phase resulted from the increasing application of the Ivor Lewis approach. Although the Ivor Lewis approach was launched on the basis of the accumulated experience from the McKeown approach, due to the change in body position and port design, the lymphadenectomy still involved a learning curve. The independent learning curves for dissecting thoracic lymph nodes using the Ivor Lewis and McKeown approaches are shown in *Figure 2*. It took 23 cases for the surgeons to accomplish the initial increase in the harvest of thoracic lymph nodes using the McKeown approach (*Figure 2A*). However, based on knowledge from the robotic McKeown lymphadenectomy, increasing the yield from

lymphadenectomy using the Ivor Lewis approach only took 18 cases (*Figure 2B*).

#### ***Comparison between McKeown RAMIE and Ivor Lewis RAMIE***

We next compared the two surgical approaches to determine if they were equivalent with regard to lymphadenectomy (*Table 3*). The mean number of total harvested lymph nodes in the learning phase of McKeown RAMIE (1<sup>st</sup> to 23<sup>rd</sup> cases) was 18.83, and that of the learning phase of Ivor Lewis RAMIE (1<sup>st</sup> to 18<sup>th</sup> cases) was also 18.83. Both surgical approaches improved the number

**Table 3** Comparison of lymphadenectomy between McKeown and Ivor Lewis RAMIE in the learning and commanding phase

Characteristics	Learning phase of			Commanding phase of		
	M-RAMIE	IV-RAMIE	P value	M-RAMIE	IV-RAMIE	P value
Age	62.17±7.08	63.44±8.77	0.610	61.67±7.38	60.00±8.77	0.491
BMI (kg/m <sup>2</sup> )	23.19±2.90	22.80±2.53	0.483	22.62±3.05	23.04±2.32	0.643
Female/male	4/19	3/15	1.000	8/38	1/12	0.668
Diabetes	1 (4.3%)	2 (11.1%)	0.573	2 (4.3%)	0 (0.0%)	1.000
Hypertension	6 (26.1%)	5 (27.8%)	0.903	12 (26.1%)	3 (23.1%)	1.000
Tumor location			0.056			0.180
Upper	5 (21.7%)	0 (0.0%)		8 (17.4%)	0 (0.0%)	
Middle and lower	18 (78.3%)	18 (100.0%)		38 (82.6%)	13 (100.0%)	
RLN-LNs	2.00±2.15	0.17±0.38	0.001	3.37±2.16	0.92±2.06	0.001
Thoracic LNs	8.22±3.24	7.56±3.07	0.511	11.96±5.38	9.38±4.11	0.117
Abdomen LNs	10.61±8.34	11.28±6.22	0.778	9.98±6.32	12.31±7.22	0.260
Total LN	18.83±9.13	18.83±7.29	0.998	21.93±8.47	21.69±7.28	0.926
T stage			0.063			0.701
T0-T2	12 (52.2%)	4 (22.2%)		22 (47.8%)	7 (53.8%)	
T3-T4a	11 (47.8%)	14 (77.8%)		24 (52.2%)	6 (46.2%)	
N stage			0.087			0.019
N0-N1	19 (82.6%)	10 (55.6%)		41 (89.1%)	8 (61.5%)	
N2-N3	4 (17.4%)	8 (44.4%)		5 (10.9%)	5 (38.5%)	
TNM stage			0.116			0.059
0-II	12 (52.2%)	5 (27.8%)		34 (73.9%)	6 (46.2%)	
III-IVa	11 (47.8%)	13 (72.2%)		12 (26.1%)	7 (53.8%)	

BMI, body mass index; LN, lymph node; RLN-LN, recurrent laryngeal nerve lymph node.

of total harvested lymph nodes after the learning phase. The mean number of total harvested lymph nodes was 21.93 in the commanding phase of McKeown RAMIE (24<sup>th</sup> to 69<sup>th</sup> cases), while it was 21.69 in the commanding phase of Ivor Lewis RAMIE (19<sup>th</sup> to 31<sup>st</sup> cases). The number of total harvested lymph nodes was comparable between the two surgical approaches in the learning and commanding phases. However, the McKeown approach harvested significantly more recurrent laryngeal nerve lymph nodes than the Ivor Lewis approach. As *Table 3* shows, the McKeown approach had more patients with tumors in the upper third esophagus. In consideration of this, we think it was the tumor location but not the surgical approach that led to more recurrent laryngeal nerve lymph nodes in McKeown cases.

## Discussion

To the best of our knowledge, this is the first study to record the actual learning course of a single surgical team from the initial start of McKeown RAMIE to mastery of both McKeown and Ivor Lewis RAMIE. Our CUSUM analysis indicated that the experienced esophageal surgical team needed to perform 23 cases of McKeown RAMIE before achieving significant improvements in the harvest of thoracic lymph nodes. Despite their thoracic lymphadenectomy experience using the McKeown approach, the transition from McKeown RAMIE to Ivor Lewis RAMIE still involved a learning curve. It took another 18 cases for the surgical team to accomplish the transition. RAMIE provides the same lymphadenectomy

quality as CMIE but could be better after the learning period.

Strengths of robot-assisted surgical systems are three-dimensional vision, articulated instruments, dexterity, and enhanced ergonomics (15,16). These allow surgeons to have a better view of the surgical field and more flexible surgical instruments. Robot-assisted surgical systems have natural advantages for performing lymphadenectomies compared with conventional thoracoscopic surgical systems. Oshikiri *et al.* reported that it took 33 cases to improve the number of total harvested lymph nodes for a team learning CMIE (17). Park *et al.* reported an increased number of harvested lymph nodes in the 28<sup>th</sup> case using RAMIE (10). In our study, a significant improvement in the number of harvested thoracic lymph nodes was achieved after the 23<sup>rd</sup> case. It took fewer cases to learn RAMIE than to learn CMIE. The shorter learning curve of lymphadenectomy using RAMIE may be due in part to the robotic surgical system itself and previous CMIE experience. To date, no study has reported the learning curve from open esophagectomy directly to RAMIE. So, we are currently unable to comment on the effect of previous CMIE experience on learning RAMIE.

The previously reported learning curve of RAMIE primarily focused on only one surgical approach (McKeown or Ivor Lewis) (18). The McKeown approach is necessary for patients with upper esophageal tumors, especially those above the carina (19). Both the McKeown and Ivor Lewis approaches are optimal for middle and lower thoracic esophageal cancer. However, the Ivor Lewis technique is less traumatic, and Yang *et al.* report better quality of life in patients who underwent Ivor Lewis esophagectomy (20). Thus, patients seeking less surgical trauma and higher quality of life will prefer the Ivor Lewis approach. For a mature robotic surgical team to be able to deal with different clinical conditions and satisfy all patients' needs, both approaches must be mastered. Therefore, while the team is learning RAMIE, experiences with both surgical approaches is imperative. A multicenter study demonstrated that there is still a learning curve for surgeons with previous experience in McKeown CMIE to master the Ivor Lewis CMIE (21). In our study, the Ivor Lewis approach was implemented in the 2<sup>nd</sup> phase and was widely launched in the 3<sup>rd</sup> phase. A decline in the CUSUM plot occurred along with the broad application of the Ivor Lewis approach in the 3<sup>rd</sup> phase. We concluded the transition from McKeown to Ivor Lewis RAMIE required another learning phase. So, a subgroup analysis

according to surgical approach was performed. The results showed it took another 18 cases for the surgeons to become proficient in thoracic lymphadenectomy using the Ivor Lewis approach. Compared with the initial learning phase for McKeown RAMIE, the following learning phase for Ivor Lewis RAMIE took fewer cases before the team became proficient at thoracic lymph node dissection.

We also compared RAMIE and CMIE to monitor the surgical quality of RAMIE. The mean number of total harvested thoracic lymph nodes in the 1<sup>st</sup> and 3<sup>rd</sup> phases were comparable to CMIE. Moreover, RAMIE harvested significantly more lymph nodes in the 2<sup>nd</sup> and 4<sup>th</sup> phases than CMIE approaches. So, the lymphadenectomy quality of the RAMIE approach was at equal to the CMIE approach, and could be better after the learning period.

There were some limitations to this retrospective study. First, this study focused on lymphadenectomy learning curves, and the learning phases were divided according to CUSUM analysis of the number of harvested thoracic lymph nodes. Other short-term outcomes, such as surgery time and postoperative complications, were not included in the analysis. So, this analysis only reflects the learning course of the lymphadenectomy, especially thoracic lymphadenectomy. Second, because of its retrospective nature, we were unable to collect the time cost of the lymphadenectomy procedure. So, we were also unable to further study improvements in the time needed for lymphadenectomy procedures.

The overall rate of neoadjuvant therapy in China is low, and in this study, only three of the 100 patients received neoadjuvant therapy. Most of our patients were from rural areas, and they had an urgent need to solve the dysphagia caused by the tumor. Thus, they had a strong preference to undergo surgery as soon as possible. Moreover, the patients were afraid of disease progression during neoadjuvant therapy that could cost them the chance for surgery. Therefore, almost all patients were unwilling to receive neoadjuvant therapy. These were the reasons why the neoadjuvant therapy rate was quite low in our patients.

In summary, our study showed the learning curve for an experienced surgical team while they mastered the McKeown and Ivor Lewis RAMIE techniques, and then analyzed interactions between learning the two surgical approaches. These lessons can be helpful and instructional for other teams learning robotic esophageal surgery. For example, surgeons who are learning or planning to learn robotic esophageal surgery techniques could know how long it normally takes before they become proficient in the



surgical approach and how the changes happened during the learning process.

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### Footnote

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*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). The study was approved by the ethics committee of West China Hospital, Sichuan University (No. 20190402). Informed consent to undergo robotic surgery without receiving financial support from the national health insurance system was obtained from all patients.

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**Table S1** Comparison of the lymphadenectomy quality between conventional MIE and RAMIE during four learning phases

Characteristics	Conventional MIE	Phase 1	P value	Phase 2	P value	Phase 3	P value	Phase 4	P value
Age	61.12±8.37	62.17±7.08	0.604	60.09±6.42	0.609	63.09±8.74	0.312	61.65±8.03	0.801
BMI(kg/m <sup>2</sup> )	22.46±3.57	23.19±2.90	0.394	22.80±2.53	0.682	22.88±4.81	0.647	23.60±3.32	0.199
Female/male	15/34	4/19	0.269	3/19	0.152	6/26	0.234	3/20	0.148
Diabetes	4 (8.2%)	1 (4.3%)	1.000	1 (4.5%)	1.000	2 (6.3%)	1.000	1 (4.3%)	1.000
hypertension	9 (18.4%)	6 (26.1%)	0.452	5 (22.7%)	0.669	11 (34.4%)	0.102	4 (17.4%)	1.000
Tumor location			0.133		0.897		0.182		0.299
Upper	4 (8.2%)	5 (21.7%)		2 (9.1%)		6 (18.8%)		0 (0.0%)	
Middle and Lower	45 (91.8%)	18 (78.3%)		20 (90.9%)		26 (81.3%)		23 (100.0%)	
Surgical approach			0.007		0.363		0.070		0.003
Ivor Lewis	12 (24.5%)	0 (0.0%)		3 (13.6%)		14 (43.8%)		14 (60.9%)	
McKeown	37 (75.5%)	23 (100%)		19 (86.4%)		18 (56.3%)		9 (39.1%)	
Histology			1.000		1.000		0.471		0.673
SCC	45 (91.8%)	21 (91.3%)		20 (90.9%)		27 (84.4%)		20 (87.0%)	
Other	4 (8.2%)	2 (8.7%)		2 (9.1%)		5 (15.6%)		3 (13.0%)	
RLN-LN	2.24±2.33	2.00±2.15	0.672	2.77±2.22	0.374	1.81±2.18	0.405	2.22±2.70	0.965
Thoracic LNs	9.96±5.20	8.22±3.24	0.088	13.05±5.64	0.027	8.66±3.61	0.221	10.61±5.28	0.625
Abdomen LNs	7.86±5.48	10.61±8.34	0.159	10.86±6.24	0.044	10.06±6.83	0.113	11.35±6.23	0.019
Total LN	17.86±7.49	18.83±9.13	0.635	23.91±7.10	0.002	18.72±8.25	0.628	21.96±7.85	0.036
T stage			0.459		0.878		0.631		0.459
T0-T2	21 (42.9%)	12 (52.2%)		9 (40.9%)		12 (37.5%)		12 (52.2%)	
T3-T4a	28 (57.1%)	11 (47.8%)		13 (59.1%)		20 (62.5%)		11 (47.8%)	
N stage			1.000		1.000		0.423		0.897
N0-N1	39 (80.0%)	19 (82.6%)		18 (81.8%)		23 (71.9%)		18 (78.3%)	
N2-N3	10 (20.0%)	4 (17.4%)		4 (18.2%)		9 (28.1%)		5 (21.7%)	
TNM Stage			0.692		0.838		0.722		0.313
0-II	28 (57.1%)	12 (52.2%)		12 (54.5%)		17 (53.1%)		16 (70.0%)	
III-IVa	21 (42.9%)	11 (47.8%)		10 (45.5%)		15 (46.9%)		7 (30.0%)	

Note: BMI= body mass index, SCC= squamous cell carcinoma, LN= lymph node, MIE= minimal invasive esophagectomy, RAMIE= robot-assisted minimal invasive esophagectomy, RLN-LN= recurrent laryngeal nerve lymph node