# Learning curve for adoption of robot-assisted minimally invasive esophagectomy: A systematic review OF ONCOLOGICAL, CLINICAL, and efficiency outcomes

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# Abstract

**Background:** Robot- assisted minimally invasive esophagectomy (RAMIE) is gaining increasing popularity as an operative approach. Learning curves to achieve surgical competency in robotic-assisted techniques have shown significant variation in learning curve lengths and outcomes. This study aimed to summarise the current literature on learning curves for RAMIE.

**Methods:** A systematic review was conducted in line with PRISMA guidelines. Electronic databases PubMed, MEDLINE, and Cochrane Library were searched, and articles reporting on learning curves in RAMIE were identified and scrutinized. Studies were eligible if they reported changes in operative outcomes over time, or learning curves, for surgeons newly adopting RAMIE.

# Results: Fifteen studies reporting on 1767 patients were included. Nine studies reported on surgeons with prior experience of robot-assisted surgery prior to adopting RAMIE, with only four studies outlining a specified RAMIE adoption pathway. Learning curves were most commonly analysed using cumulative sum control chart (CUSUM) and were typically reported for lymph node yields and operative times, with significant variation in learning curve lengths (18-73 cases and 20-80 cases respectively). Most studies reported adoption without significant impact on clinical outcomes such as anastomotic leak; significant learning curves were more likely in studies which did not report a formal learning or adoption pathway.

**Conclusion:** Reported RAMIE adoption phases are variable, with some authors suggesting significant impact to patients. With robust training through formal programmes or proctorship, however, others report RAMIE adoption without impact on clinical outcomes. A formalised adoption curriculum appears critical to prevent adverse effects on operative efficiency and patient care.

# Introduction

Minimally invasive and robot-assisted techniques are being increasingly employed in radical esophagectomy1. The advantages of a minimally invasive approach have been well described in other areas of surgery2–5. With the advance of surgical technique and technology, this shift in practice in esophagectomy has been supported by limited randomised trials to date; these have suggested a reduced incidence of postoperative pulmonary complications in minimally invasive esophagectomy (MIE)6–8. The ROBOT trial, comparing robotic- assisted minimally invasive esophagectomy (RAMIE) to open esophagectomy, demonstrated reduced post-operative complications, better short-term quality of life and comparable oncological outcomes in the robotic cohort9. Early results from the RAMIE trial, comparing RAMIE with MIE, has shown significantly shorter operation times in RAMIE, with improved efficiency of thoracic lymph node dissection in patients who received neoadjuvant therapy10.

While such surgical advances may undoubtedly benefit patients, it has been well documented that learning curves seen during the adoption and learning phase of any new technique may detrimentally impact patient outcome11–14. The surgical learning curve has been described as the rapid change in performance over time seen with the adoption of a new technique15. This encompasses (1) the starting point, defined by the individual’s own experience and ability, (2) the slope / curve, defined by the rate and magnitude of performance change, and (3) plateau, where incremental performance improvements become insignificant, and the surgeon may be considered experienced at the task at hand.

The significant increase in anastomotic leak and re-intervention rates during the implementation of conventional MIE, observed in the national Dutch Upper Gastrointestinal Cancer Audit (DUCA) database, illustrates the ethical and clinical risks of rapid uptake with new techniques16. Some of the efforts to prevent such events have included national training programmes, as seen in the transition from open to laparoscopic colorectal surgery17, centralisation of care to promote higher volumes18–22, and public outcome reporting23,24. A previous systematic review of learning curves in robotic-assisted surgery across ten specialities, not including esophageal surgery, reported significant variation in learning curve lengths and outcomes12.

RAMIE is currently undergoing a critical phase of rapid proliferation. Esophagectomy represents a procedure already routinely associated with high post-operative morbidity and significant disease recurrence rates; it is vital that any change to surgical approach does not negatively impact patient outcomes during the initial adoption phase25. By understanding the magnitude of any associated learning curve, and identifying interventions to abbreviate or ameliorate it, surgical care may continue to be advanced with patients confident that their outcomes will not be compromised.

This systematic review aims to summarise the current literature reporting on learning curves for RAMIE. It aims to describe the length of learning curve and factors which might affect this, including prior surgical experience or technique, training or proctorship programme, and any impact on outcomes.

**Methods**

**Search strategy**

A systematic review was conducted in accordance with PRISMA guidelines but was not formally registered26. PubMed, MEDLINE, and Web of Science databases were searched from database inception up to the 31st May 2022. The following search terms and MeSH headings were used and combined with Boolean operands ‘‘AND’’ and ‘‘OR’’ as shown: (‘‘esophagectomy’’ OR ‘‘esophagus” OR ‘‘esophag\*” OR “esophag\*”) AND (‘‘robotics” OR ‘‘robotic surgical procedures’’ OR ‘‘robot\*’’) AND (“learning curve” OR “learn\*” OR adoption). Following removal of duplicates, initial screening of titles and abstracts identified articles of interest, which then underwent full-text analysis and data extraction. Reference lists of retrieved articles were hand-searched for additional relevant references. The search was conducted by 2 researchers (P.H.P. and O.P.) with any discrepancies resolved by consensus.

**Selection criteria**

Eligible studies included any studies that reported changes in outcome over time, or learning curve, for surgeons newly adopting RAMIE. Studies reporting only changes in technique, with associated outcomes, for surgeons already practicing RAMIE, were excluded. No specific criteria for previous robotic experience were used. Review articles or conference abstracts were not included.

**Outcomes and data synthesis**

Data was extracted from eligible studies and collated in Microsoft Excel (Microsoft Corp., Redmond. WA). Captured data included study design, method of determining the learning curve, robotic technology used, part of procedure performed robotically (abdominal phase, thoracic phase or both), number of surgeons, surgeon experience prior to adoption of RAMIE, and method of introduction of RAMIE technique (e.g. proctoring programme, wet-lab cases). Operative outcomes including major morbidity and 30-day mortality were collated with oncological outcomes including lymph node yield and R0 resection status. The number of procedures to overcome the learning curve (as defined by the authors of each study) were captured. Learning curves for different outcome types were considered:

* Oncological efficacy: lymph node yields (total lymph nodes and/or thoracic lymph nodes)
* Surgical efficiency: total operative time
* Patient safety: blood loss, morbidity (30-day morbidity rates, major morbidity defined as Clavian Dindo grade ≥ 3), anastomotic leak rates, and vocal cord paralysis rates.

Missing data from each study has been highlighted, with summary statistics describing only those studies where relevant data was reported. No data conversion was necessary.

**Study quality assessment**

Study quality was assessed using the Newcastle-Ottawa Scale for cohort studies27. Scores ranging from 0 to 9 were assigned based on several methodological factors including the study sample’s representativeness of the exposed cohort as well as methods used to confirm exposure and comparability of the cohorts. Studies with seven or more points were considered to be of good quality. Studies with four to six were scored as moderate quality and studies with three or less points were scored as poor quality.

**Results**

A total of 61 search results were returned and screened for eligibility (Figure 1). Following review of titles and abstracts 28 articles were retrieved and reviewed in full. Of these, 15 were included in the final dataset.

*Study Demographics*

Characteristics of the 15 included studies are presented in Table 1. All included studies were consecutive case series reporting on a total of 1767 patients who underwent RAMIE for esophageal cancer. A total of 17 surgeons were included. Twelve of the included studies described a single surgeon experience, with two studies reporting on two surgeons. Van der Sluis et al. include outcomes for an experienced robotic surgeon and a learning curve analysis of a second surgeon introduced to RAMIE through a formal proctoring program28.

Prior experience before adoption of the robotic approach was reported in 13/15 studies. Two studies described a transition from an open thoracic approach with no prior thoracoscopic experience, the remaining 11 studies were from centres with significant prior experience of MIE.

*Robotic Approach*

Ivor Lewis (2-phase) RAMIE was the predominant surgical approach in 5 studies, with McKeown (3-stage) esophagectomy being used in 9 studies. The remaining study reported starting with a McKeown approach and then transitioning to Ivor Lewis esophagectomy after sufficient experience was gained. The robotic platform was used for a totally robot-assisted approach (both chest and abdominal phases) in 9 studies, with robotic use in the chest phase only in 6 studies. Twelve out of the fifteen studies utilised the da Vinci robotic platform (Intuitive Surgical, Sunnyvale, California, USA), whilst Park et al, Sarkaria et al and Zhuo et al did not report their robotic systems.

There did not appear to be any observable differences between reported learning curves for studies utilising a totally robot-assisted approach compared with studies using a robotic chest phase only. However, variations in study sample sizes, methods for learning curve analysis, adoption strategies and prior surgical experience may mask any impact of variations in robotic approach.

*Adoption of Robotic Approach*

Nine studies reported prior experience of robot-assisted surgery prior to adopting RAMIE. Three reported no prior robotic experience at all prior to implementation of RAMIE (Table 2). van der Sluis et al. and Park et al. report their included surgeons had assisted in 20 or more RAMIEs prior to technique adoption28,29. Zhang et al. report prior experience of a single benign case and Sarkaria et al. report performance of a single cadaveric procedure30,31. By contrast, Kingma et al. report prior experience of 10 benign robotic cases and Fuchs et al. report their included surgeons had undertaken two preparation modules on the robot and had performed 30 benign upper gastrointestinal cases prior to adopting RAMIE32,33.

Only four studies reported their adoption pathway for RAMIE. The remainder did not report any specific process.

Only Han et al. specifically declared that their adoption of RAMIE was undertaken without any specific educational programme; the authors also reported no prior robotic experience prior to starting RAMIE (though they did report “significant” previous MIE experience).

van der sluis at el. report the learning curves for a newly introduced surgeon who was proctored by a senior surgeon who had experience with >150 RAMIEs28. After 20 procedures as assisting table surgeon and 5 observational cases during the proctor program, the surgeon performed 15 RAMIE procedures under strict supervision by the proctor.

Fuchs et al. describe a modular approach to adoption of RAMIE33. A totally robotic-assisted transthoracic esophagectomy was divided in to 6 modules starting with gastric mobilisation and finishing with esophagogastric anastomosis. The two included surgeons could progress to the next module when they subjectively felt confident with the current module.

Kingma et al. made use of the structured Upper GI International Robotic Association (UGIRA) RAMIE training pathway32 which describes the 3 adoption phases of preparation (case observation, robotic training, initial performance of less complex robotic cases), initiation (at least 2 cases proctored by an experienced surgeon), and implementation (independent practice with monitoring of outcomes).

*Operative outcomes*

Summary of overall operative outcomes for consecutive cases performed by surgeons newly introduced to RAMIE is presented in Table 3. Median or mean lymph node yield was reported in 7 studies and ranged from 17.4 to 46.5 total lymph nodes. Thirty-day morbidity rates ranged from 26.9% to 85%, with major morbidity rates (Clavian Dindo grade ≥ 3) ranging from 20 to 26% and anastomotic leak rates from 1.9% to 26%. Thirty-day mortality rates varied from 0 to 5%.

*Learning curves for oncological outcomes*

The most common method of assessing learning curves was the cumulative sum (CUSUM) method. CUSUM plots increases or decreases in a given outcome, compared to the mean, for sequential cases; a visual inflection point is identified where a plateau phase for outcome is reached and the initial learning curve has been overcome.

The number of operative cases to complete the learning curves for lymph node yield and operative times are summarised in table 4.

Most (11/15) included studies reported learning curve data for lymph node yields, of which 73% (8/11) reported a statistically significant increase in nodal yields over the course of procedure adoption, with an inflection point between 18-73 cases.

Park et al. compared outcomes for the first 20 RAMIE cases against the subsequent 13 cases29. The authors found no learning curves in operative times (338 vs 370 mins) or number of dissected lymph nodes around the recurrent laryngeal nerves (RLN) (right RLN 4.55 vs 4.83, left RLN 6.25 vs 5.42).

*Efficiency outcomes*

Operative times were analysed in 14/15 studies, with 79% (11/14) reporting a learning curve illustrating a significant reduction in operative times with increasing experience, with an inflection point between 20-80 cases.

Grimminger et al. did not report learning curves but compared 3 consecutive cohorts of 25 patients who underwent hybrid esophagectomy, MIE, or RAMIE 34. Authors reported significant differences in operative times (mean 314, 338, 410 min, respectively). Mean hospital (15.8, 17.2, 21.8 days) and ICU (2.8, 3.4, 9.7 days) length of stays were longest for RAMIE but were not statistically significant between the 25 patient cohorts. Reported morbidity rates (Clavien Dindo ≥ 3; 32%, 25%, 32%) and oncological outcomes (mean lymph node yields; 26.2, 25, 24.5) were similar.

When analysing outcomes for the first 232 RAMIEs performed by a current proctor, Van der sluis et al. report conversion rates in the thoracic phase of the procedure of 20% (14/70) in the first 70 cases, significantly reducing to 3% (2/58) between cases 175 to 23228. No differences were seen in conversion rates in the abdominal phase over the same operative case intervals.

Fuchs et al. report a modular approach to RAMIE adoption33. After 30 benign cases and 10 esophagectomies to work through the defined operative modules, both included surgeons were proficient enough to complete all of RAMIE with no further learning curve for operative time. There were no operative conversions.

*Clinical outcomes*

Reported learning curves for blood loss, morbidity, anastomotic leak, and vocal cord palsy rates are detailed in table 5.

Nine of the fifteen studies (60%) analysed learning curves for mean operative blood loss, of which 4/9 (44%) reported significantly reduced blood loss over the course of procedure adoption, with an inflection point reported between 22-70 cases.

van der Sluis at el. report the learning curves for both a newly introduced surgeon undertaking a robotic proctoring programme and for the senior surgeon acting as a proctor28. The senior surgeon saw an inflection point for mean blood loss at case 70 (500 vs 360mls). The junior surgeon under proctor guidance had a much lower inflection point at 24 cases.

Sarkaria et al. compared outcomes between the first 50 and last 50 cases, reporting a significant reduction in median blood loss (300 vs. 200mL), although no inflection point was analysed.

Learning curves for 30-day morbidity were analysed in 9/15 (60%) of studies, of which 3/9 (33%) report significant reductions in morbidity, with inflection points between 21-51 cases.

Ten studies (67%) analysed learning curves for anastomotic leak rates, of which only 2 (20%) demonstrated significant reductions over the course of procedure adoption, with inflection points between 80-82 cases.

Learning curves for vocal cord paralysis (VCP, associated with intrathoracic high mediastinal nodal dissection close to the recurrent laryngeal nerve) rates were analysed in 8/15 (53%) studies. Five studies (5/8, 63%) report significant reductions in VCP rates, with inflection points between 12-80 cases. Most notable are the outcomes from Park et al. who report a significant reduction in VCP rates from 55% to 0 after 20 cases, without impacting nodal yield around the RLNs29.

*Quality assessment*

All the included studies were rated as moderate quality, with Newcastle- Ottawa scores ranging from 4 to 6. Study quality was limited by the lack of independent assessment of outcomes (such as post-operative complications and blood loss), adjustment for patient factors during learning curve analysis and specified follow up duration and adequacy.

**Discussion**

This review summarises the current evidence on learning curves in the adoption of RAMIE, offering important data during the current period of rapid expansion of this technique. The rapid progression of surgical technology and techniques has in the past threatened to be detrimental to patients, as eager adoption of new methods has outpaced the availability appropriate training or regulation, potentially negatively impacting outcomes35. This review suggests there is huge variation in the experience levels and adoption pathways for units and surgeons starting RAMIE, and that this may have significant implications for patients. Conversely, we highlight a number of studies that have reported uncomplicated adoption pathways; understanding and replicating such outcomes will be required if robot-assisted surgery is to be broadly adopted in esophago-gastric surgery.

The presence and magnitude or length of learning curves was highly variable, illustrated by the significant range in learning curves for operative time from 20-80 cases. The differences in study sample sizes and methods for learning curve analysis may, in part, account for these large variations. Hernandez et al, reported a learning curve of 20 cases for total operative time, calculated by comparing consecutive 10-patient cohorts in a sample of 52 patients. By contrast Park et al, reported a learning curve of 80 cases using CUSUM analysis in a sample of 140 patients. Neither study outlined their previous robotic experience or pathway for robotic adoption which may have further explained the large differences in learning curve.

Only a minority of studies reported appreciable learning curves for safety-related outcomes such as morbidity (3/9 studies) or anastomotic leakage (2/10). The two studies reporting significant learning curves for anastomotic leak reported curves of 80 and 82 cases respectively – if these findings were generalisable, such case volumes in many Western centres could take individual surgeons years to accrue. Importantly, neither of these studies (Yang et al, Park et al (2018)) reported any prior robotic experience or any formalised adoption program. The remaining vast majority of studies, in contrast to these two studies, reported no appreciable learning curves for leaks, suggesting it is entirely feasible to adopt RAMIE in a fashion which was not detrimental to patients who were operated on during the adoption phase. This observation may reflect the use of standardised anastomotic techniques, such as the use of circular stapler-anastomosis, which the surgeons are already familiar with from their prior experience with MIE. However, most studies reported reduced lymph node yields during the introductory phase which subsequently increased. While some controversy remains as to the implication of nodal harvest counts and its association with oncological efficacy or long-term survival, this may indicate initial operations are being performed to a lesser level of radicality, with unclear implications for patient long-term outcomes36.

In many centres, esophagectomy is still being performed open and it is unclear whether experience in laparoscopic or thoracoscopic approaches may be of benefit when transitioning to RAMIE37. Hernandez et al, for example, reported “extensive” prior experience with MIE prior to adopting RAMIE38. Authors reported no appreciable learning curve for morbidity or anastomotic leak, and a relatively short learning curve of only 20 cases for operative time. Park et al (2017) and Fuchs et al both transitioned directly from open surgery to RAMIE; however, both undertook structured training programmes with Park observing and assisting 50 RAMIEs, and Fuchs completing a modular structured training pathway first29,33. Park et al (2017) reported a learning curve for VCP (20 operative cases) but no learning curves for other oncological, temporal, and clinical outcomes. Fuchs at el did not detect a learning curve for operative times.

The findings of this review emphasise the crucial nature of a structured adoption pathway for centres adopting RAMIE, and the ability of such a program, ideally including formal proctorship, to ameliorate learning curves even in the hands of a previously experienced non-robotic surgeon. Similar findings have been reported in laparoscopic colorectal surgery, whereby delegates participating in a ‘train the trainers’ curriculum to improve, standardise, and benchmark the quality of their training techniques found the learning curves of their trainees improved39. While a structured training pathway (typically including modular training, multiple case observations and assists, and surgical proctoring) was reported by only a small number of studies included in this review, it is unsurprising that these reported some of the best results (i.e. lack of appreciable learning curves for reported outcomes). Conversely, the only study to bravely declare that RAMIE was adopted without prior robotic experience and without any training program, reported significant learning curves of up to 50 or more cases for all relevant outcomes, strongly suggesting that these initial patients may have been done a disservice in their surgical approach40.

Similar variability in learning curves have been reported in other specialities12. A systematic review of learning curves for operative times for robotic lung resections reported a curve between 14- 60 cases, with no significant differences seen when comparing studies who reported prior experience in either thoracoscopic or thoracotomy approaches41. Similarly, huge variations were seen in a review of robot-assisted laparoscopic prostatectomies, with reported learning curves of 50-200 cases for operative times and 50-1600 cases for positive surgical margin rates respectively, the latter being influenced by differences in the authors’ definitions of positive margins42. By contrast, a review of robotic rectal surgery revealed narrower learning curves ranges, with inflection points between 15-35 cases for operative times43.

Analyses of learning curves are fraught with difficulties, owing to the multiple factors impacting learning curve lengths such as operative frequency during technique adoption and prior experience of the surgeon and surrounding team44. It has long been known that clinical outcomes are poor proxies for operative proficiency due to numerous confounding factors affecting outcome measures45. In esophageal cancer, these are not limited to the patient factors such as anatomy, body habitus and previous surgery impacting operative complexity, available equipment, surgical and anaesthetic approaches, patient rehabilitation, post-operative care setting (intensive care or ward base) and adherence to enhanced recovery pathways46–49. These factors are poorly, or not at all, controlled for. Selection and reporting bias is likely in any adoption phase for new techniques. However, in the absence of easily obtainable non-clinical metrics, operative time remains the most commonly used in learning curve analysis in minimally invasive surgery12,44. An absence of standards for reporting of learning curve data further limits the generalisability of such studies12,50.

The ethical considerations surrounding learning curves are complex. Whilst formal training programmes and simulation techniques may reduce learning curve lengths, a period of suboptimal performance during technique adoption may be unavoidable17,35,39,51. The impact of this goes beyond hospital outcome metrics but has significant consequences to patients. Specifically in esophageal cancer, reduced operative performance risks adding to the already significant long-term burden following esophagectomy, with reduced lymph node yields potentially impacting disease-free survival and post-operative complications risking earlier cancer recurrence and reduced survival rates36,52,53. Particularly in Western practice, where surgeons in all but the highest-volume centres are likely to perform a limited (<15-20) number of esophageal resections annually, learning curves of the extent reported by some of the studies included here would be likely to take years of practice to overcome.

If learning curves cannot be completely eliminated, a negative impact on outcomes, beyond the obvious impact on patients, could also feasibly disincentivise the progression of surgical techniques. Whilst the introduction of national or international patient outcome reports such as the UK National Oesophago-gastric Cancer Audit (NOGCA), or Upper GI International Robotic Association (UGIRA) registry have increased transparency in surgical outcomes, only the DUCA audit is mandatory23,54. It remains unclear what may happen to surgeons or centres that have been identified as performance outliers23. This becomes even more difficult when considering that some of these surgeons may be on a learning curve during adoption of MIE or RAMIE. An ‘acceptable’ reduction in operative performance during transition to a new technique has not been defined. Equally, the obligations of the robotic manufacturers to train and audit outcomes requires clarification. Whilst the leading manufacturers can coordinate and finance complex curricula and proctored training for clients, there is currently no consensus on credentials required to deliver a robotic training programme. Manufacturers currently accept no responsibility for the training process and have not yet supplied open access data for users’ robotic console metrics. The latter may be invaluable in determining learning curves for robot adoption. Finally, with several new robotic platforms now available, it remains unclear what impact these will have on operative learning curves.

This systematic review is limited by the quality of the included studies, inconsistency in reporting of outcomes and differences in the methods used to determine learning curve lengths. Standardisation of learning curve analysis will be crucial to exploring the effects of procedure adoption in future studies.

**Conclusion**

This study provides a comprehensive summary of the existing literature around the learning curves in RAMIE. RAMIE adoption is possible with minimal impact on clinical outcomes, subject to robust training through formal programmes or proctorship, together with governance and audit of outcomes. Optimal strategies to ameliorate learning curves are unclear and should be an area of focus for future research. Key to this will be standardisation of learning curve reporting.

**Disclosure**

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