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ORIGINAL ARTICLE – GASTROINTESTINAL ONCOLOGY

Quality Improvement in Minimally Invasive Esophagectomy: Outcome Improvement Through Data Review

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ABSTRACT

Background. Esophagectomy is a complex operation in which outcomes are profoundly influenced by operative experience and volume. We report the effects of experience and innovation on outcomes in minimally invasive esophagectomy.

Methods. Esophageal resections for cancer from 2007 to 2016 at Levine Cancer Institute at Carolinas Medical Center (Charlotte, NC) were reviewed. During this time, three changes in technique were made to improve outcomes: vascular evaluation of the gastric conduit to improve anastomotic healing (beginning at case #63), one-stage approach to permit access to abdomen and chest through one draped surgical field (case #82), and adoption of a lung-protective anesthetic protocol (case #101). Mortality, operative time, complications, and length of stay were analyzed relative to these interventions using GLM regression.

Results. 200 patients underwent minimally invasive esophagectomy. There were no mortalities at 30 days, and no change in mortality rate at 60 and 90 days. Anastomotic leak decreased significantly after the introduction of intraoperative vascular evaluation of the gastric conduit (3.6 vs 19.4%). Operative time decreased with adoption of a one-stage approach (416 vs 536 min). Pulmonary complications decreased coincident with a change in anesthetic technique (pneumonia 6 vs 28%). Lymph node harvest increased over time. Length of stay was driven primarily by complications and decreased with operative experience.

Conclusions. Postoperative complications, operative time, and length of stay decreased with case experience and alterations in surgical and anesthetic technique. We believe that adoption of the techniques and technology described herein can reduce complications, reduce hospital stay, and improve patient outcomes.

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Esophagectomies are among the most invasive procedures performed. Minimally invasive techniques have been introduced to improve outcomes,[1–4] while reports of hospital surgical volume and patient outcomes[5] have demonstrated a clear link between outcomes and volume in complex procedures.[5–8] As surgeons and hospitals perform more operations, surgical proficiency and outcomes improve.

This study presents the maturation of a minimally invasive esophagectomy program through the adoption of new technology and techniques.

METHODS

Approval and waiver of informed consent were obtained from the Carolinas HealthCare System Institutional Review Board. Data from 212 consecutive patients undergoing esophagectomy from 2007 to 2016 at Levine Cancer Institute at Carolinas Medical Center (Charlotte, NC) were analyzed. Patients with benign disease ($n = 9$), or treated with a transhiatal approach ($n = 2$), or planned total esophagectomy with colon interposition ($n = 1$) were excluded, resulting in a cohort of 200 patients.

Three major changes to technique were adopted in response to periodic outcomes reviews. The first was vascular evaluation of the gastric conduit to improve anastomotic healing (initiated at case #63).[9] Second was introduction of a one-stage, single-position, Ivor Lewis approach (as opposed to two-stage approach), beginning at case #82.[10] Third was intraoperative lung-protective anesthesia designed to reduce pulmonary complications (case #101).[11]

The two-stage operative technique was previously published,[12] and is similar to the approach described by Bizekis, Pennarthur,[13,14] and Nguyen.[15] Anesthesia is induced with a double-lumen endotracheal tube. After laparoscopic mobilization of the greater curvature, the left gastric artery is divided and associated nodes harvested. The conduit is constructed intracorporeally with a linear stapler. Gastric drainage is performed. The gastric conduit is examined with fluorescent angiography using indocyanine green and Doppler to evaluate the blood supply of the stomach.[9] A jejunostomy tube is placed routinely. The patient is repositioned in left lateral decubitus position, prepped and draped for the thoracic stage. One-lung anesthesia is initiated. The esophagus is mobilized and divided with a linear stapler. Frozen section of the proximal margin is obtained, and once a negative margin is confirmed, the decision to resect additional esophagus is made based upon the available length of well-vascularized conduit based upon its vascular evaluation. A flip-top stapler anvil attached to an orogastric tube (OrVil™, Covidien, North Haven, CT, USA) is introduced through the mouth, and the anvil brought out through a fenestration in the esophageal staple line. A circular stapler (DST Series™ EEA™ XL stapler, Covidien, North Haven, CT, USA) is introduced into the conduit, and the anastomosis constructed.

The one-stage operative approach has been previously described.[10] The patient is positioned supine with the upper torso and shoulders rotated to the left. The right scapula is supported on a lateral positioner, and the right arm brought across the chest. The abdomen, right chest, and right axilla are prepped into the field. The table is rotated to the right for the laparoscopic phase, which is identical to the initial portions of the two-stage approach. The table is rotated to the left, and the right chest entered. Thoracoscopic dissection and division of the esophagus is performed, and the distal esophagus and specimen delivered through the hiatus to the abdomen. The table is rotated back to the right, and the stomach and distal esophagus are exteriorized for extracorporeal construction of the conduit, which is facilitated by the ability to place the stomach (and staple line) on tension. In addition, this approach allows palpation of the gastroesophageal junction, minimizing the risk of a positive distal margin.[16] The table is again rotated to the left, and the anastomosis is constructed in the chest.

The protocol for lung-protective anesthesia consisted of low ventilation pressures with 5–8 cm positive end-expiratory pressure (PEEP) and 3–5 cm continuous positive airway pressure (CPAP) of the operative lung.

Patient demographics, tumor characteristics, staging information,[17] treatment information, operative factors, operative time, length of stay, and complications were analyzed relative to operative experience. Patient characteristics are summarized in Table 1, comparing cases 1–100 versus cases 101–200 using Chi square test for categorical and Kruskal–Wallis for continuous variables.

Outcomes were analyzed by comparing groups before and after each intervention. Anastomotic leak and anastomotic stricture rates were compared before and after case #63, when vascular evaluation of the conduit was introduced. Operative times were compared between the two- and one-stage surgical approach. Pulmonary complications were compared before and after introduction of a lung-protective anesthetic protocol at case #101. Groups were compared using univariate GLM analysis. For complications, logistic regression was used; for operative time, linear regression. CUSUM charts were utilized to identify proficiency gains as described.[18,19] The R changepoint package was used to analyze the CUSUM change point where outcome improvement began.

Outcomes not specifically targeted by quality improvement intervention were analyzed using case number as a continuous variable to reflect operative experience. Lymph node harvest was analyzed with Poisson regression, and length of stay with linear regression using a log transformation, given the skewed nature of the data. For descriptive purposes, these outcomes are presented in Table 2, comparing cases 1–100 versus cases 101–200.

To investigate the effect of other factors on outcomes, multivariable GLM models were constructed. Demographics, smoking, histology, staging, preoperative therapy, surgical approach, surgical technique, and open surgery were examined using univariate analyses. The StepAIC R package for automatic model selection was used to create a final multivariable model.

In all cases, unadjusted values (Table 2) are reported from univariate models and adjusted values (Tables 3, 4) from final multivariable models. For categorical covariates in the final models with more than two levels, contrasts are shown for each level relative to a reference level. Analyses were conducted with R version 3.3.2 (http://www.R-project.org/).

TABLE 1 Demographics and characteristics of patients undergoing minimally invasive esophagectomy for cancer (n = 200)

	Cases 1–100	Cases 101–200	p Value
Age (years), median [range]	63 [33, 81]	65 [30, 83]	0.03*†
Sex, no. (%)			0.72
Male	79 (79.0)	82 (82.0)	
Female	21 (21.0)	18 (18.0)	
BMI, median [range]	27.8 [16.8, 45]	27.8 [19.0, 43.5]	0.91
Race, no. (%)			1.00
Caucasian	89 (89.0)	92 (92.0)	
Black	11 (11.0)	7 (7.0)	
Asian	0	1 (0.01)	
Income quintile (based upon zip code)			
Quintile 1 (lowest)	19 (19.0)	23 (23.0)	0.15
Quintile 2	15 (15.0)	23 (23.0)	
Quintile 3	19 (19.0)	24 (24.0)	
Quintile 4	24 (24.0)	13 (13.0)	
Quintile 5 (highest)	23 (23.0)	17 (17.0)	
Histology, no. (%)			0.31
Adenocarcinoma	87 (87.0)	89 (89.0)	
Squamous cell carcinoma	12 (12.0)	11 (11.0)	
Neuroendocrine carcinoma	1 (1.0)	0 (0.0)	
Insurance status, no. (%)			0.24
Commercial or medicare	93 (93.0)	87 (87.0)	
Medicaid or uninsured	7 (7.0)	13 (13.0)	
Smoking history, no. (%)			0.70
Nonsmoker	14 (14.0)	17 (17.0)	
Smoking history	86 (86.0)	83 (83.0)	
Clinical T, no. (%)			0.33
T1	21 (21.0)	13 (13.0)	
T2	12 (12.0)	14 (14.0)	
T3	67 (67.0)	73 (73.0)	
Clinical N, no. (%)			0.68
N0	59 (59.0)	57 (57.0)	
N1	39 (39.0)	39 (39.0)	
N2	2 (2.0)	3 (3.0)	
N3	0 (0.0)	1 (1.0)	
Clinical M, no. (%)			1.00
M0	99 (99.0)	100 (100.0)	
M1	1 (1.0)	0 (0.0)	
Pathologic T, no. (%)			0.88
T0	18 (18.0)	19 (19.0)	
T1	32 (32.0)	29 (29.0)	
T2	19 (19.0)	13 (13.0)	
T3	31 (31.0)	39 (39.0)	
Pathologic N, no. (%)			0.39
N0	56 (56.0)	65 (65.0)	
N1	27 (27.0)	24 (24.0)	
N2	14 (14.0)	7 (7.0)	
N2	3 (3.0)	4 (4.0)	

TABLE 1 continued

	Cases 1–100	Cases 101–200	p Value
Pathologic M, no. (%)			1.00
M0	98 (98.0)	100 (100.0)	
M1	2 (2.0)	0 (0.0)	
Neoadjuvant treatment, no. (%)			
None	26 (26.0)	20 (20.0)	
Yes (chemotherapy or chemoRT)	74 (74.0)	80 (80.0)	
Neoadjuvant treatment, no. (%)			0.06
None	28 (28.0)	19 (19.0)	
Chemotherapy alone	6 (6.0)	1 (1.0)	
Chemoradiation	66 (66)	80 (80.0)	
Neoaduvant chemoRT, no. (%)			0.07
None	34 (34.0)	20 (20.0)	
ChemoRT	66 (66.0)	80 (80.0)	
Neoadjuvant treatment type, no. (%)			< 0.01*
None	28 (28.0)	20 (20.0)	
Carboplatin + paclitaxel + radiation	39 (39.0)	73(73.0)	
Other neoadjuvant therapy	33 (33.0)	7 (7.0)	
Margin status, no. (%)			0.45
R0	95 (95.0)	91 (91.0)	
R1	5 (5.0)	7 (7.0)	
R2	0 (0.0)	1 (1.0)	
Surgical approach, no. (%)			< 0.001*
Two-stage approach	82 (82.0)	1 (1.0)	
One-stage approach	18 (18.0)	99 (99.0)	
Thoracic approach, no. (%)			0.77
Planned thoracotomy	3 (3.0)	1 (1.0)	
Thoracoscopy	91 (91.0)	94 (94.0)	
Conversion to thoracotomy	6 (6.0)	5 (5.0)	
Abdominal approach, no. (%)			1.00
Planned laparotomy	1 (1.0)	0 (0.0	
Laparoscopy	98 (98.0)	98 (98.0)	
Conversion to laparotomy	2 (2.0)	2 (2.0)	
Preoperative feeding tube, no. (%)			0.04*
No	68 (68.0)	49 (49.0)	
Yes	32 (32.0)	51 (51.0)	
Gastric drainage procedure, no. (%)			< 0.001*
None	3 (3.0)	0 (0.0)	
Pyloromyotomy	13 (12.0)	66 (66.0)	
Pyloroplasty	47 (45.0)	18 (18.0)	
Balloon dilation	1 (1.0)	1 (1.0)	
Botulinum toxin	36 (36.0)	15 (15.0)	

*Significant at $p < 0.05$

†Kruskal–Wallis. All other tests performed with Chi square

TABLE 2 Outcomes of patients undergoing minimally invasive esophagectomy (n = 200)

			p Value
Conduit vascular evaluation	No	Yes	
GI complications, no. (%)			
Anastomotic leak	12 (19.4)	5 (3.6)	< 0.001*
Stricture	12 (19.4)	8 (5.8)	0.009*
Surgical approach	Two-stage	One-stage	
Operative time, median [range]	536 [399, 823]	416 [294, 743]	< 0.001*
Lung-protective anesthesia	No	Yes	
Pulmonary complications, no. (%)			
Pneumonia	28 (28.0)	6 (6.0)	<0.001*
ARDS	12 (12.0)	4 (4.0)	0.047*
Prolonged ventilation	23 (23.0)	9 (9.0)	0.010*
Tracheostomy requirement	15 (15.0)	6 (6.0)	0.044*
Case experience	Cases 1–100	Cases 101–200	
Mortality, no. (%)			
30-day + in-hospital	1 (1.0)	2 (2.0)	>0.99
60-day + in-hospital	2 (2.0)	4 (4.0)	0.68
90-day + in-hospital	3 (3.0)	5 (5.0)	0.72
Length of stay, median [range]	12 [7, 109]	9 [5, 60]	< 0.001*
Lymph node harvest, median [range]	12 [1, 36]	16.5 [5, 43]	< 0.001*
Positive histologic margins, no (%)	5 (5.0)	8 (8.0)	0.340
Cardiovascular complications, no. (%)			
Atrial arrhythmia	23 (23.0)	23 (23.0)	0.49
Myocardial infarction	2 (2.0)	1 (1.0)	0.80
Pulmonary embolism	4 (4.0)	2 (2.0)	0.81
Central nervous system event	3 (3.0)	2 (2.0)	0.49
Other complications, no. (%)			
New-onset renal failure	2 (2.0)	0 (0.0)	0.54
Readmission to ICU	4 (4.0)	6 (6.0)	0.16
Readmission within 30 days	17 (17.0)	13 (13.0)	0.63

ARDS acute respiratory distress syndrome, *ICU* intensive care unit

*Significant at $p < 0.05$. Results from univariate (unadjusted) generalized linear method (GLM)

RESULTS

A total of 200 patients met inclusion criteria. The median age was 64 years (range 30–83 years), and the majority were male (81%) or Caucasian (91%). Patients largely presented with adenocarcinoma (88%); fewer presented with squamous cell (11.5%) and neuroendocrine (0.5%) carcinomas. Neoadjuvant chemotherapy and radiation was administered to 73% of patients, neoadjuvant chemotherapy alone to 3.5%, and no preoperative therapy in 23%. The nature of the preoperative therapy changed during the study period. A total of 153 patients received neoadjuvant therapy, of whom 112 received carboplatin/paclitaxel with radiation, beginning at case #25 after the publication of the CROSS trial in 2010. Other patient characteristics are listed in Table 1.

Mortality

There were no mortalities at 30 days. In-hospital deaths were 1% in the first 100 cases and 2% in the second 100 cases (unadjusted $p > 0.99$). Sixty-day and 90-day all-cause mortality did not significantly change over the study period. Sixty-day all-cause mortality (including hospital deaths) was 2% in the first 100 cases and 4% in the second 100 cases (unadjusted p =0.68), and 90-day all-cause mortality (including hospital deaths) was 3% in the first

TABLE 3 Multivariable predictors of complications and mortality (n = 200)

Complication variables	β	SE	*p* Value
Anastomotic leak			
Open surgery	1.848	0.778	0.017
Stapler size (25 mm)	− 3.102	0.915	<0.001*
TNM pathologic T classification	− 0.580	0.335	0.08
TNM pathologic N classification	1.333	0.713	0.06
Conduit vascular evaluation	− 1.471	0.616	0.017*
Anastomotic stricture			
Gender (female)	0.941	0.580	0.105
Histology (ref = adenocarcinoma)			
Squamous cell carcinoma	1.425	0.672	0.033*
Neuroendocrine carcinoma	− 12.85	882.7	0.985
Clinical TNM node classification	1.342	0.570	0.019*
Pathologic TNM node classification	− 1.501	0.661	0.023*
Conduit vascular evaluation	− 1.208	0.553	0.029*
Stapler size (25 mm)	− 1.804	0.927	0.052
Pneumonia			
Age	0.052	0.261	0.046*
Smoking (ref = nonsmoker)	1.119	0.820	0.147
Gender (female)	− 0.858	0.630	0.173
Race (ref = White)			
Black	1.958	0.634	0.002*
Asian	18.93	1455	0.990
Lung-protective anesthesia	− 2.293	0.564	<0.001*
Prolonged ventilation			
Age	0.101	0.033	0.002
Race (ref = White)			
Black	2.649	0.6935	<0.0001
Asian	20.3	1455	0.989
Income (quintile)	− 0.317	0.175	0.07
Thoracotomy	1.248	0.745	0.09
Gastric drainage (ref = pyloroplasty)			
Pyloromyotomy	− 1.354	0.777	0.08
Other	0.513	0.528	0.33
Lung-protective anesthesia	− 1.095	0.607	0.07
Tracheostomy			
Age	0.116	0.045	0.010
Race (ref = White)			
Black	1.857	0.882	0.035
Asian	25.61	10,754	0.998
Preoperative feeding tube	− 1.015	0.657	0.122
Open surgery	2.187	0.818	0.007
Gastric drainage (ref = pyloroplasty)			
Pyloromyotomy	− 1.159	0.988	0.107
Other	1.72	0.679	0.011
Lung-protective anesthesia	− 1.148	0.758	0.130
Adult respiratory distress syndrome (ARDS)			
Age	0.057	0.038	0.128
Smoking (ref = nonsmoker)	16.85	1784	0.992
Race (ref = White)			
Black	1.418	0.793	0.052
Asian	23.43	10,754	0.998
Thoracotomy	1.398	0.720	0.052
Lung-protective anesthesia	− 1.743	0.734	0.012*

*Significant at $p < 0.05$. For significant categorical variables with more than two levels, contrasts are shown

100 cases and 5% in the second 100 cases (unadjusted p =0.72).

Introduction of Vascular Evaluation of the Conduit

Anastomotic leak decreased after introduction of vascular evaluation of the conduit at case #63 from 19.4 to 3.6% (p <0.001 unadjusted GLM; p =0.017 adjusted; Tables 2, 3). Immediately after the introduction of vascular evaluation of the conduit, 30 consecutive cases were performed without leak.[9] By CUSUM change point analysis, this improvement occurred after case #62 (Fig. 1a). Clinically significant anastomotic strictures requiring endoscopic dilation also decreased at this time from 19.4 to 6.5% (p <0.009 unadjusted GLM; p =0.029 adjusted). Change point analysis showed that the rate of stricture began to decrease after case #62 as well (Fig. 1B).

Introduction of One-Stage Surgical Approach

Operative time was significantly shorter in patients undergoing a one-stage approach (p <0.001 unadjusted). For two-stage operations (earlier in the experience), median operative time was 536 min compared with 416 min in one-stage operations (Table 2). On multivariable analysis, patients undergoing open surgery had significantly longer operative time, as did those who underwent total esophagectomy with cervical anastomosis. Operative time was longer in patients with squamous cell carcinoma and those with elevated BMI. Female patients had shorter operative time, as did those receiving preoperative chemoradiation. The one-stage approach was associated with shorter operative time on adjusted analysis (p <0.001, Table 4). After adjusting for other factors, operative experience continued to be an independent predictor of operative time (p =0.012 adjusted). When patients were stratified by operative approach, operative experience was associated with shorter operative time for the two-stage approach (primarily cases 1–82) (p = 0.043 on univariate GLM) but not for the one-stage approach (p = 0.62 on univariate GLM).

Adoption of Lung-Protective Anesthetic Management

Rate of pneumonia decreased after adoption of lung-protective anesthetic management at case #101 (6 vs 28%, p <0.001 unadjusted, p <0.001 adjusted; Tables 2, 3). Rates of prolonged postoperative ventilation (> 48 h) were also reduced (9 vs 23%). This was a significant change on univariate analysis (p =0.01 unadjusted, Table 2), but not on multivariable analysis (p = 0.07 adjusted, Table 3). In both cases, CUSUM change point analysis demonstrated that the rate began to decrease after case #97 (Fig. 1c, d). Tracheostomy placement did not appear significantly affected by change in anesthetic management (6 vs 15%, p =0.044 unadjusted, p = 0.13 adjusted). CUSUM change point analysis revealed that the rate began to decrease after case #129. The risk of acute respiratory distress syndrome (ARDS) was decreased with lung-protective anesthesia (4 vs 12%, p =0.047 unadjusted, Table 2; p = 0.012 adjusted, Table 3). The study cohort contained one Asian patient who experienced pneumonia, ARDS, prolonged ventilation, and tracheostomy and subsequently died. Analyses were reanalyzed after excluding this patient, and results were unchanged.

Operative Experience, Lymph Node Harvest, and Length of Stay

Postoperative atrial arrhythmia, pulmonary embolism, myocardial infarction, stroke, new-onset renal failure, and readmission rate did not change over the operative experience (Table 2). Margin positivity did not change with experience (8 vs 5%, p = 0.34 unadjusted, Table 2).

Lymph node harvest was higher in patients with higher case number (median 17 vs 12, p <0.001 unadjusted, p =0.015 adjusted; Tables 2, 4) and with a one-stage surgical approach. Lymph node harvest was lower in patients receiving preoperative chemoradiation.

Length of stay decreased with operative experience (median 9 vs 12 days, p <0.001 unadjusted, p <0.001 adjusted). On multivariable analysis, other significant predictors of increased length of stay included increasing age, Black race, and postoperative complications (anastomotic leak, pneumonia, and tracheostomy; Table 4).

DISCUSSION

Even in the era of minimally invasive esophagectomy, morbidity and complications remain significant issues. Through a process of periodic review of outcomes and innovations in technique, we have been able to significantly reduce morbidity and improve patient outcomes while reducing resource utilization.

There have been numerous studies reporting single-institution experience with both open and minimally invasive esophagectomy to describe outcome improvement over time, or the "learning curve."[2,15,20–30] Markar and colleagues examined proficiency gains in open esophagectomies in Sweden and found that gains came at different points with experience. Improvements in 30-day mortality came within the first 15 cases, whereas long-term mortality improved between cases 35 and 59. Margin positivity decreased after 17 cases, and lymph node harvest continued to increase with case number.[25]

Proficiency gains occurred in a similar fashion to that described by Markar. We previously reported our early reduction in mortality compared with institutional historical controls after introduction of the minimally invasive esophagectomy program with zero all-cause mortalities at 30 days within the first 32 cases.[12] This reduction in mortality was sustained throughout our experience.

Reported rates of anastomotic leak after minimally invasive esophagectomy are highly variable (2.7–20%).[29,31–33] We initiated use of Doppler and intraoperative indocyanine green angiography at case #63 to evaluate the vascular supply of the conduit.[9] This resulted in a significant reduction in anastomotic leak. Immediately after introduction of these techniques, none of the next 30 patients suffered anastomotic leak. Case #63 was also identified on CUSUM as the point after which the rate of anastomotic leak began to decrease (Fig. 1A). Anastomotic stricture has been reported to occur in as many as 25% of cases. After the introduction of evaluation of the vascular supply, the rate of stricture significantly decreased, presumably due to better healing of the anastomosis as a result of adequate vascular supply.

Operative time has also been reported as a benchmark of proficiency. Prolonged operative time has also been associated with inferior outcomes across different surgical disciplines.[34–36] Some series reporting minimally invasive esophagectomy have found that operative time decreased significantly after the first 17–20 cases.[1–3,28] Others reported reduction in operative time with experience, though a specific number of cases was not identified.[29,37] On multivariable analysis, operative time was significantly longer with conversion to open surgery and total esophagectomy with cervical anastomosis. Increased BMI was associated with longer operative time. Operative time

TABLE 4 Multivariable predictors of operative time, lymph node harvest, and length of stay (n = 200)

Outcome variable	β	SE	p Value
Operative time			
Gender (female)	− 40.17	14.51	0.006*
BMI	5.525	1.042	<0.001*
Histology (ref = adenocarcinoma)			
Squamous cell carcinoma	50.55	14.51	0.007*
Neuroendocrine carcinoma	6.86	77.51	0.93
Preoperative chemoradiation	− 30.23	12.72	0.018*
One-stage approach (ref = two-stage)	− 57.78	19.42	0.003*
Open surgery	75.86	19.48	<0.001*
Total esophagectomy (cervical anastomosis)	216.3	39.65	<0.001*
Operative experience (rank of case number)	− 0.423	0.1655	0.012*
Lymph node harvest			
Income quintile	− 0.020	0.013	0.127
Insurance status (Medicaid or uninsured)	0.208	0.058	<0.001*
Histology (ref = adenocarcinoma)			
Squamous cell carcinoma	− 0.235	0.062	<0.001*
Neuroendocrine carcinoma	− 1.916	0.709	0.006
TNM clinical node classification	− 0.121	0.042	0.003
Chemoradiation	− 0.095	0.047	0.044*
One-stage approach (ref = two-stage)	0.142	0.067	0.032*
TNM pathologic node classification	0.145	0.039	<0.001*
Operative experience (rank of case number)	0.001	0.005	0.015*
Length of stay			
Age	0.008	0.002	0.001
Race (ref = White)			
Black	0.237	0.084	0.001*
Asian	0.343	0.317	0.28
Open surgery	0.128	0.081	0.11
Anastomotic leak	0.495	0.080	<0.001*
Pneumonia	0.267	0.075	<0.001*
Prolonged ventilation (> 48 h)	0.179	0.092	0.053
Tracheostomy	0.721	0.103	<0.001*
Operative experience (rank of case number)	− 0.001	0.0003	<0.001*

*Significant at $p < 0.05$. For significant categorical variables with more than two levels, contrasts are shown for each level

was shorter with the one-stage approach, likely due to elimination of the need to reposition and re-prep. After accounting for these factors, however, operative experience was still significantly associated with shorter operative time (Table 4). When patients were stratified by operative technique, operative experience was associated with shorter operative time for the two- but not one-stage technique. This difference is likely due to the fact that the one-stage technique was used later in our experience, after the "learning curve" had flattened out.

Apart from anastomotic leak, pneumonia is a major factor in postoperative complications after esophagectomy.[3,37–39] It has also been suggested that, as experience increases, pneumonia rate decreases.[2] After review of our pulmonary outcomes, a lung-protective strategy for intraoperative ventilatory management was adopted at case #101.[11] Adoption of this strategy coincided with a reduction in pneumonia and prolonged ventilation (Fig. 1c, d; Tables 2, 3).

Nodal harvest improved gradually over our experience, consistent with what was reported by Markar.

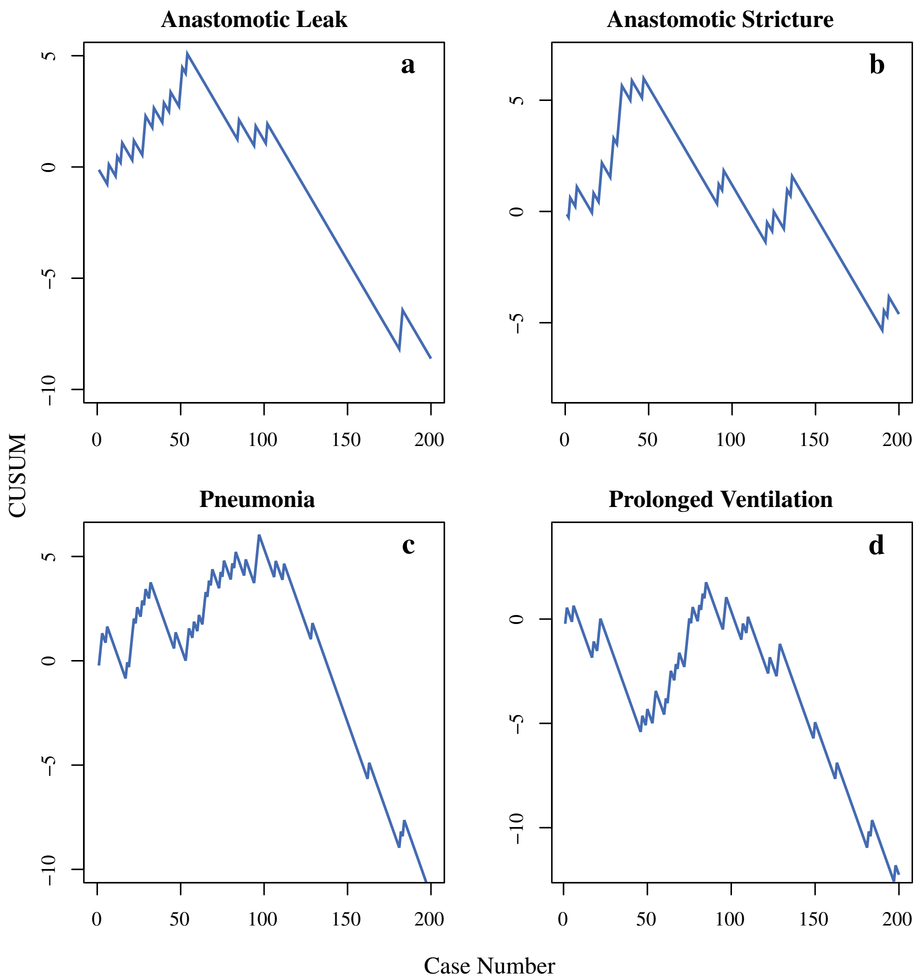

FIG. 1 CUSUM charts of complications as a function of case number

Length of stay decreased during the study period with operative experience. On multivariable analysis, increased age, race, complications, and operative experience were independently associated with length of stay.[40]

This study has limitations common to studies in which clinical practice changes during the study period. Although the changes in clinical practice and operative experience were clearly associated with improved outcomes, it is not certain that these changes were responsible for the improved outcomes. During the study period, there were other changes which may have influenced the rate of postoperative complications, notably the type of neoadjuvant chemoradation. A total of 154 patients received neoadjuvant therapy, of whom the majority (115) received carboplatin and paclitaxel with radiation therapy, beginning at case #25. Multivariable analyses, however, failed to demonstrate that any of the improvements in outcomes were a result of changes in neoadjuvant therapy regimens. On the other hand, operative experience was associated with decreases in leak rate, anastomotic stricture, pulmonary complications, and length of stay, and increases in lymph node harvest.

Utilization of new technology, innovation in technique, increase in experience, and leveraging available outcome data have helped mature our minimally invasive esophagectomy program and dramatically improve outcomes for our patients.

CONCLUSIONS

Postoperative complications and operative time decreased over the course of our experience. The most dramatic improvements occurred with adoption of new technology and techniques. The optimization of outcomes for patients undergoing esophagectomy in our institution was the result of multidisciplinary preoperative planning, the operation itself, and postoperative care. We believe that adoption of the techniques and technology described herein may reduce complications, reduce cost, and improve patient outcomes.

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