Thoracoscopic esophagectomy for esophageal cancer: Feasibility and safety of robotic assistance in the prone position

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Objective: To assess the feasibility and safety of robot-assisted thoracoscopic esophagectomy for esophageal cancer in the prone position.

Methods: Twenty-one patients underwent robot-assisted thoracoscopic esophagectomy in the prone position by a surgical oncologist who had no prior experience with thoracoscopic esophagectomy. Hemodynamic and respiratory parameters were serially recorded to monitor changes in prone positioning.

Results: All thoracoscopic procedures were completed with a robot-assisted technique followed by cervical esophagogastrostomy. R0 resection was achieved in 20 patients (95.2%), and the number of dissected nodes was 38.0 ± 14.2 . Robot console time was significantly reduced from 176.3 ± 12.3 minutes in the initial 6 patients (group 1) to 81.7 ± 16.5 minutes in the latter 15 patients (group 2) ($P = .000$). In group 2, there was less blood loss ($P = .018$), more patients could be extubated in the operating room ($P = .004$), and the number of dissected mediastinal nodes tended to be increased ($P = .093$). There was no incidence of pneumonia or 90-day mortality. Major complications included anastomotic leakage in 4 patients, vocal cord palsy in 6 patients, and intra-abdominal bleeding in 1 patient. The prone position led to an elevation of central venous pressure and mean pulmonary arterial pressure and a decrease in static lung compliance. However, cardiac index and mean arterial pressure were well maintained with the acceptable range of partial pressure of arterial oxygen and carbon dioxide.

Conclusion: Robotic assistance in the prone position is technically feasible and safe. Prone positioning was well tolerated, but preoperative risk assessment and meticulous anesthetic manipulation should be carried out. (J Thorac Cardiovasc Surg 2010;139:53-9)

Supplemental material is available online.

Thoracoscopic esophagectomy (ThE) has been performed in patients with esophageal cancer to reduce morbidity and mortality while preserving oncologic quality of the resection. Recent large series have reported a low incidence of pneumonia and mortality, whereas the medium-term, stage-specific survival was similar to reports from open esophagectomy.¹⁻³ However, ThE necessitates a substantial amount of learning, even for experienced thoracoscopic surgeons.⁴

Robot-assisted surgery has the potential to accelerate the learning curve of minimally invasive esophagectomy (MIE) because it has several advantages, including increased magnification with 3-dimensional view, articulation of

instruments, improved dexterity, and better ergonomics.⁵ Although the robotic system has been introduced to ThE,^{6,7} its role and potential advantages have yet to be verified.

We started robot-assisted ThE as our first MIE program in 2006. The prone position was used because it is known to facilitate mediastinal dissection and minimize lung injury.² We hypothesized that, owing to robotic assistance and advantages of the prone position, we could transfer our surgical strategy from open transthoracic esophagectomy to MIE within a short learning period. The objective of this study was to assess the feasibility and safety of robot-assisted ThE for esophageal cancer in the prone position.

MATERIALS AND METHODS

Following 5 cases of robot-assisted surgeries for benign mediastinal tumors, robot-assisted ThEs were performed in the prone position by a single thoracic surgeon (DJK). At the time of study design, the surgeon had a low surgical volume (<4 open Ivor-Lewis operations per year) with no prior experience with MIE. A prospective data registry was used to collect clinical data, and the study was approved by the institutional review board of Yonsei University College of Medicine, Seoul, Korea.

Patients

Between July 2006 and January 2008, 25 patients with intrathoracic esophageal cancer were seen by the same thoracic surgeon. Of these, 2 patients with multiple, bulky nodal metastases underwent definitive chemoradiation; 1 patient with calcified pleural thickening underwent open

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Abbreviations and Acronyms

CI	= cardiac index
CVP	= central venous pressure
MIE	= minimally invasive esophagectomy
MPAP	= mean pulmonary arterial pressure
Pao ₂	= partial pressure of arterial oxygen
Paco ₂	= partial pressure of arterial carbon dioxide
pkAWP	= peak airway pressure
plAWP	= plateau airway pressures
ThE	= thoracoscopic esophagectomy

transthoracic esophagectomy, and 1 patient with suspicious margin involvement by tumor after endoscopic submucosal dissection refused surgery. Thus, 21 consecutive patients underwent robot-assisted ThE in the prone position.

Preoperative endoscopic biopsy was performed in all patients to confirm the histologic diagnosis of esophageal cancer. Staging workup included thorough history and physical examination, esophagogastroduodenoscopy, endoscopic ultrasonography, and integrated positron emission tomography/computed tomography scan. Operative risk was assessed by a composite risk score based on general health status, cardiopulmonary function, and other organ functions.⁸ Demographic data of patients are listed in Table 1.

Surgical Approach

Indications for surgery were similar to those for open surgery. For resectable clinical stage I to III tumors, curative intent surgery was performed followed by adjuvant chemotherapy or chemoradiation therapy according to pathologic stage. Induction chemoradiation is not a routine protocol for a resectable lesion at the Yonsei University College of Medicine. Salvage esophagectomy was performed in selected patients who presented a good response to definitive chemoradiation. Regardless of the aim of surgery, the same surgical principle was applied. En bloc esophagectomy with extended mediastinal lymphadenectomy was performed, followed by gastric mobilization with upper abdominal lymph node dissection and cervical esophagogastrotomy. When a primary lesion was located at the upper thoracic esophagus or the upper paraesophageal lymph node was involved in middle or lower thoracic esophageal cancer, bilateral cervical lymphadenectomy was added.

The patient was intubated with a Univent bronchial blocker tube (Fuji Systems Corp, Tokyo, Japan) and turned to the prone position. Beanbags were placed under the chest and pelvis to leave the abdomen free. Four trocars were placed with inspection of the pleural space after carbon dioxide (CO₂) insufflation at 8 to 10 mm Hg: a 12-mm trocar at the 8th intercostal space for a 30-degree angled, 10-mm thoracoscope; an 8-mm trocar at the 6th intercostal space medial to the scapula for a right robotic arm; an 8-mm trocar at the 10th intercostal space for a left robotic arm; and a 12-mm trocar at the 9th intercostal space along the anterior axillary line for the accessory port (Figure E1). After docking of the da Vinci robotic cart (Intuitive Surgical, Mountain View, Calif) from the left cranial side of the patient, the right lung was collapsed with a bronchial blocker and dissection began. The arch of the azygos vein was isolated and divided by an endoscopic linear stapler. The mediastinal pleura overlying the esophagus was incised, and the upper thoracic esophagus was circumferentially mobilized from the trachea with caution to avoid injury to the membranous portion of the trachea (Figure E2). Dissection continued down to the mid-thoracic esophagus, and the vagal trunk was cut below the level of its pulmonary branch. The left side of the esophagus was dissected by incising the left pleura. The thoracic duct, mediastinal pleura, and lymph nodes at the paraesophageal, subcarinal, and peribronchial stations were dissected to remain en bloc with the esophagus. Then, the infra-aortic nodes were dissected

TABLE 1. Demographics of patients

Operative risk profile		Oncologic data	
Age, y	61.5 ± 9.6	Location	
Sex, M/F	18/3	Upper	3 (14.3%)
Body mass index, kg/m ²	20.0 ± 2.9	Middle	7 (33.3%)
		Lower	11 (52.4%)
Karnofsky index		Histology	
100	3 (14.3%)	Squamous	20 (95.2%)
90	12 (57.1%)	Adenocarcinoma	1 (4.8%)
≤ 80	6 (28.6%)	Initial stage at diagnosis	
Smoking history*	9 (42.9%)	I	12 (57.1%)
Alcohol abuse	6 (28.6%)	IIA	2 (9.5%)
COPD	2 (9.5%)	IIB	2 (9.5%)
Hypertension	5 (23.8%)	III	3 (14.3%)
Ischemic heart disease	2 (9.5%)	IV†	2 (9.5%)
Pulmonary function test			
FEV ₁ , % of normal	105.1 ± 21.6	Preoperative treatment	
FVC, % of normal	93.9 ± 16.9	None	18 (85.7%)
		Chemoradiation	3 (14.3%)
Operative risk‡			
Low	15 (71.4%)	Intent of surgery	
Moderate	5 (23.8%)	Curative	18 (85.7%)
High	1 (4.8%)	Salvage	3 (14.3%)

COPD, Chronic obstructive pulmonary disease; FEV₁, forced expiratory volume in 1 second; FVC, forced vital capacity. *Smoking history > 20 pack-years. †Operative risk for postoperative morbidity and mortality according to the composite risk score.⁸

‡Classified as M1 due to non-regional lymph node metastasis.

(Figure E3), and the lymph nodes along the left recurrent laryngeal nerve were sampled systematically. A 28F chest tube was placed, and the collapsed right lung was inflated. The patient was then turned to the supine position. Gastric mobilization, tube formation, and celiac axis lymph node dissection were performed by a gastric surgeon (WJH). A laparoscopy was performed in 14 patients, robot-assisted technique was performed in 4 patients, and laparotomy was performed in 3 patients with a history of multiple intra-abdominal operations. We constructed a 3- to 4-cm-wide, narrow gastric tube without pyloroplasty. At the end of the abdominal phase, a left cervicotomy was made and the cervical esophagus was mobilized. A horizontal collar incision was chosen when bilateral cervical lymphadenectomy was indicated. The esophagogastric specimen was pulled out through a neck incision under laparoscopic control. Esophagogastric anastomosis was performed with side-to-side stapled anastomosis in 19 patients and circular-stapled anastomosis in 2 patients.

We recorded the operation time at each step of the procedure. *Pre-robot time* started from the skin incision for trocar placement and ended at the docking of the robot cart and loading of robot arms. *Console time* started from the initiation of dissection with the robot and ended at the completion of the thoracic phase. *Total operation time* started from the skin incision for trocar placement in the thoracic phase and ended at the skin closure of the neck and abdominal wounds.

Postoperative Care

All patients were transferred to the intensive care unit for monitoring. The nasogastric tube was removed on the second postoperative day, and esophagography was done on the seventh postoperative day. For patients without anastomotic leakage, diet was advanced to soft diet for 2 to 3 days, and then they were discharged. Analgesia was achieved by intravenous patient-controlled analgesia for 2 days and then by fentanyl skin patch (25 µg/h) for 4 to 6 days. Postoperative complications were graded in accordance with the National Cancer Institute's Common Terminology Criteria for Adverse Events, version 3.0.⁹

Monitoring of Hemodynamic and Respiratory Parameters

Prospective monitoring of hemodynamic and respiratory parameters was performed to assess the effects of the prone position. A Swan-Ganz catheter (Edwards Life Sciences LLC, Irvine, CA) was inserted into the right internal jugular vein in all patients. Heart rate, mean arterial pressure, central venous pressure (CVP), mean pulmonary arterial pressure (MPAP), and cardiac index (CI) were recorded. Respiratory parameters such as static compliance of the lung, peak airway pressure (pkAWP), plateau airway pressure (plAWP), partial pressure of arterial oxygen (Pao₂), and partial pressure of arterial carbon dioxide (Paco₂) were also monitored. During the procedure, constant anesthetic technique was applied using sevoflurane inhalation with infusion of remifentanyl (0.1–0.3 µg/kg/min). The ventilation setting was (1) tidal volume, 8 mL/kg; (2) respiration rate, 10 to 12 breaths/min; (3) fraction of inspired oxygen, 1.0; and (4) positive end-expiratory pressure, 0 cm H₂O.

Hemodynamic and respiratory parameters were measured in the supine position (T0), 20 minutes after prone positioning (T1), 20 minutes after the initiation of 1-lung ventilation (T2), and 20 minutes after repositioning to supine (T3). A pressure transducer was adjusted to the level of the right atrium and calibrated after each position change.

To eliminate bias from the variable operation time in the initial cases, analysis was performed in patients in whom the robot console time reached a plateau. Exclusion criteria for the analysis included (1) use of inotropics, (2) excessive bleeding requiring blood transfusion, and (3) fluid resuscitation to maintain vital signs.

Statistical Analysis

SPSS statistical software (version 12.0; SPSS Inc, Chicago, Ill) was used for statistical analysis. Descriptive statistics of the quantitative variables are presented as mean ± standard deviation. Statistical analysis included Mann–Whitney test and Fisher's exact test. Changes in quantitative measures for hemodynamic and respiratory parameters were compared within each point (T0–T1, T1–T2, and T2–T3) by Wilcoxon signed-rank test. All *P* values are 2-sided.

FIGURE 1. Total operation time and robot console time in order of experience. After the initial 6 cases, robot console time reached a plateau with a mean value of 81.7 ± 16.5 minutes.

RESULTS

Operation Data

All thoracoscopic procedures were completed with the robot-assisted technique. Eighteen of 21 patients (85.7%) underwent operation with curative aim. Salvage esophagectomies were performed in 2 patients who showed a good response to chemoradiation for advanced lesion and in 1 patient who presented a local recurrence with nodal metastasis at 2 years after endoscopic submucosal dissection. Bilateral cervical lymphadenectomy was carried out in 6 patients (28.6%). The mean number of all dissected lymph nodes was 38.0 ± 14.2 (median, 40; range,

TABLE 2. Surgical outcomes

	Total (n = 21)	Group 1 (n = 6)	Group 2 (n = 15)	P value
Operation time, min				
Total	410.0 ± 99.6	542.8 ± 36.1	356.9 ± 14.5	.000
Pre-robot	16.6 ± 9.6	21.2 ± 4.3	14.8 ± 10.6	.002
Robot console	108.8 ± 46.3	176.3 ± 12.3	81.7 ± 16.5	.000
No. of dissected lymph nodes				
Mediastinal	11.6 ± 6.2	8.3 ± 3.1	12.9 ± 6.7	.093
Abdominal	21.1 ± 9.8	20.2 ± 9.8	21.5 ± 10.1	.876
Intraoperative blood loss, mL*	150 (50–2300)	250 (200–2300)	160 (50–500)	.018
No. of patients extubated at OR	11 (52.4%)	0 (0.0%)	11 (73.3%)	.004
Chest tube stay, d*	5 (2–11)	5 (2–11)	5 (1–9)	.501
ICU stay, d*	2 (1–3)	2 (1–3)	1 (1–3)	.121
Hospital stay, d*	21 (11–45)	25 (13–45)	21 (11–36)	.413
Complications				
Cervical anastomotic leakage	4 (19.0%)	2 (33.3%)	2 (13.3%)	—
Anastomotic stricture	2 (9.5%)	1 (16.7%)	1 (6.7%)	—
Vocal cord palsy	6 (28.6%)	2 (33.3%)	4 (26.7%)	—
Chylous ascites	1 (4.8%)	0 (0.0%)	1 (6.7%)	—
Intra-abdominal bleeding	1 (4.8%)	1 (16.7%)	0 (0.0%)	—
Atrial fibrillation	1 (4.8%)	0 (0.0%)	1 (6.7%)	—
Pneumonia or atelectasis	0 (0.0%)	0 (0.0%)	0 (0.0%)	—
90-d mortality	0 (0.0%)	0 (0.0%)	0 (0.0%)	—

OR, Operating room; ICU, intensive care unit. *Median (range).

15–67). R0 resection was achieved in 20 patients (95.2%). Resection was incomplete in 1 patient who had microscopic residual disease at the right deep neck node near the recurrent laryngeal nerve. Final pathologic stage was stage I in 8 patients (38.1%), IIB in 5 patients (23.8%), III in 4 patients (19.1%), IVA in 1 patient (4.8%), IVB in 2 patients (9.5%), and pathologic complete response in 1 patient (4.8%). Eleven patients (52.4%) received adjuvant therapy based on pathologic stage (chemotherapy in 6 patients, chemoradiation in 4 patients, and radiation therapy in 1 patient).

Surgical Outcome

Total operation time was 410.0 ± 99.6 minutes, and robot console time for the thoracic phase was 108.8 ± 46.3 minutes. Robot console time reached a plateau after 6 cases of operation as shown in Figure 1. It was significantly reduced from 176.3 ± 12.3 minutes in the initial 6 cases (group 1) to 81.7 ± 16.5 minutes in the latter 15 cases (group 2) ($P = .000$). Surgical outcomes of the 2 groups are listed in Table 2. Operation time was shorter, there was less blood loss, and more patients could be extubated in the operating room in group 2. The number of dissected mediastinal lymph nodes tended to be increased in group 2, but the statistical difference was not significant. Hospital stay was prolonged in both groups because of several complications. Four patients presented with cervical anastomotic leakage (grade II in 3 patients and grade III in 1 patient), and 2 patients had anastomotic stricture (grade III in both) that required repeated endoscopic balloon dilatations. Six patients experienced vocal cord palsy (grade II in 4 patients and grade III in 2 patients) that recovered within 3 months. There was 1 case of massive bleeding from the splenic hilum that required a laparotomy (grade IV). Other complications included transient atrial fibrillation (grade I in 1) and chylous ascites (grade II in 1), but there was no incidence of postoperative pneumonia, atelectasis, or operative mortality.

Changes in Hemodynamic and Respiratory Parameters in the Prone Position

Hemodynamic and respiratory parameters were analyzed in group 2 as the robot console time reached a plateau (Figure 2). No patients in group 2 met the exclusion criteria, whereas 2 patients in group 1 needed inotropic support or intraoperative blood transfusion. The prone position led to elevation of both CVP and MPAP at T1, and they were further elevated by applying 1-lung ventilation at T2. At T3,

when patients were turned to the supine position after completion of the thoracic phase, these values returned to baseline values at T0. However, both CI and mean arterial pressure showed relatively constant levels with no significant alterations throughout the procedure. More notable findings were observed in respiratory parameters. Both pkAWP and plAWP increased as static lung compliance decreased in the prone position at T1, whereas Pao₂ and Paco₂ showed no significant alterations. When 1-lung ventilation was applied in the prone position at T2, static compliance decreased significantly below 50% of the baseline value. This change caused a marked increase in pkAWP and plAWP with a decrease in Pao₂ and an elevation in Paco₂ at T2. As opposed to hemodynamic changes, static lung compliance remained decreased and plAWP remained elevated at T3 compared with baseline levels at T0. At T3, neither Pao₂ nor Paco₂ recovered to baseline values, but their absolute values were within an acceptable range.

DISCUSSION

ThE with extended mediastinal lymphadenectomy is a technically demanding procedure because the 2-dimensional monitor cannot give perspective of the operative field and the rigid instruments have limitations in accessing all aspects of periesophageal structures. The principal finding of this study is the potential role of a robotic system to achieve an adequate learning curve by a low-volume surgeon who had no prior experience with ThE. All thoracic procedures were completed thoracoscopically with robotic assistance, and we did not encounter any incidence of pneumonia, respiratory failure, or 90-day mortality. In a systematic review by Decker and colleagues,¹⁰ centers reporting fewer than 25 cases of MIE had a 3.9% mortality rate, 30.8% respiratory complication rate, and 9.6% conversion rate. In addition, robot console time and number of dissected mediastinal nodes are comparable to other large series. Although data on thoracoscopy time are limited, it ranged from 75 to 223 minutes according to the experience of the surgeon and extent of lymph node dissection.^{4,11–14} We harvested 11.6 ± 6.2 lymph nodes from the mediastinum in 108.8 ± 46.3 minutes of console time, which is comparable to 4,¹¹ 7,¹² 12,¹³ and 19.7¹⁴ nodes in other series. Smithers and colleagues,³ in the largest available series of 309 ThEs performed over 11 years, reported that they retrieved 7 mediastinal nodes in 90 minutes of thoracoscopy time. Considering that this is our first MIE series, which was contemplated by a low-volume surgeon, the overall result

FIGURE 2. Changes in hemodynamic and respiratory parameters. *Significant difference between 2 points; $P < .05$. ↓ The measured value at T3 is significantly different from its baseline value at T0; $P < .05$. HR, Heart rate; SD, standard deviation; CVP, central venous pressure; MPAP, mean pulmonary arterial pressure; CI, cardiac index; MAP, mean arterial pressure; Comp, static compliance of the lung; pkAWP, peak airway pressure; plAWP, plateau airway pressure; Pao₂, partial pressure of arterial O₂; Paco₂, partial pressure of arterial CO₂; T0, baseline in the supine position; T1, 20 minutes after prone positioning; T2, 20 minutes after initiation of 1-lung ventilation; T3, 20 minutes after repositioning to supine.

seems to be acceptable in terms of operative time, number of dissected mediastinal lymph nodes, pulmonary complication rate, and mortality.

We also observed a steep learning curve reflected in a rapidly diminishing robot console time. Robot console time was significantly reduced after only 6 cases, and this led to a reduction in total operation time with a resultant high percentage of immediate extubation in group 2. In addition, the amount of blood loss was lower and the number of dissected mediastinal lymph nodes tended to be increased in group 2. Osugi and colleagues⁴ reported in their series of 80 ThEs that a plateau in technique was not reached until 34 cases had been performed. The shortened learning curve with the use of the robotic interface was reported by some authors.^{5,15} Ahlering and colleagues⁵ demonstrated that they only needed 10 cases to achieve 4-hour proficiency in robot-assisted radical prostatectomy, whereas it required 40 to 60 cases in conventional laparoscopic surgery. How could the robotic system affect the learning curve in ThE? Possible explanations are as follows. First, the robot interface offers a 3-dimensional view that is familiar to all surgeons, and it eliminates the perceptual problems of a 2-dimensional monitor. Second, intrapleural articulation of instruments allows for better reach during extended mediastinal lymphadenectomy, which is particularly useful in dissecting the left side of the esophagus with mediastinal lymph nodes en bloc. It also eliminates the fulcrum effect of rigid instruments. Third, the motion scaling and tremor filtering function allows for meticulous dissection of lymph nodes compared with the conventional thoracoscopic procedure in which a minor tremor is intensified through the long, rigid shaft.

However, early achievement of comparable proficiency in the thoracic phase did not always reflect a good postoperative outcome. If any complication occurs during the cervical or abdominal phases, it could countervail the benefits of robotic assistance in the thoracic phase. For example, cervical anastomotic leakage occurred in 19% of patients, which is higher than in other studies.¹⁻⁴ One possible reason is the use of a narrow gastric tube, which has been known to increase anastomotic complications.¹⁶ Considering that Orringer and colleagues¹⁷ achieved a 13% leakage rate in their series of 1085 patients, we expect a decrease in anastomotic leakage as we gain more experience and adopt a wider gastric tube. We also need to decrease the rate of vocal cord palsy that is associated with extensive nodal dissection and cervical anastomosis. Although our patients experienced only transient hoarseness, it may cause frequent aspiration and subsequent pneumonia. We believe that inexperience in cervical esophageal mobilization and nodal dissection may be the main cause of this because the surgeon had experience with only 2-field dissection and intrathoracic anastomosis before this series. The use of hook cautery during node

dissection along the left recurrent laryngeal nerve might be another cause of nerve injury. These complications resulted in prolonged hospital stay, showing that we need more experience in the cervical and abdominal phases to achieve the overall benefits of MIE.

The prone position is known to offer several advantages in esophagectomy: Lung injury is minimized because lung retraction is not necessary because of gravity, bleeding does not obscure the operative field, and exposure of the infra-aortic area and tracheobronchial tree is excellent.^{2,11} However, the effects of the prone position in MIE have not been clearly demonstrated. We recorded hemodynamic and respiratory changes before, during, and after the prone position. Mean arterial pressure, CI, and heart rate were well maintained throughout the procedure, whereas CVP and MPAP were elevated at T1 and T2. An elevation of CVP and MPAP at T1 was caused by increased intrathoracic pressure from the chest wall splinting, and 1-lung ventilation was attributed to a further elevation at T2. There has been controversy on the change in CI in the prone position. Most studies were performed in patients undergoing lumbar spine surgery, and a decrease in CI was almost a universal finding as Backofen and Schauble¹⁸ reported a 24% decrease in CI in 16 patients. One study using transesophageal echocardiography showed that CI did not change, although CVP was increased slightly.¹⁹ However, the operative setting seems to be more important as Yokoyama and colleagues²⁰ demonstrated that the flat position did not interfere with circulatory function, whereas the position using a convex saddle frame caused a decrease in CI. On a convex saddle frame, the position of the heart above the head and limbs may have caused reduced venous return and decreased CI. We used a flat table with beanbags placed under the chest and pelvis. In this setting, elevation of abdominal pressure is minimized and venous return is not severely compromised. Respiratory parameters showed more notable changes that have clinical implications. Although static lung compliance decreased in the prone position with elevation in $pkAWP$ and $plAWP$, Pao_2 and $Paco_2$ were well maintained. This could be explained by an increase in functional residual capacity and improvement in ventilation/perfusion matching in the prone position.^{21,22} However, initiation of 1-lung ventilation caused a marked reduction in static compliance and a decrease in Pao_2 with retention of carbon dioxide. A more important finding is that these changes at T2 were not fully recovered at 20 minutes after repositioning to the supine. We can assume that 1-lung ventilation may induce some degree of alveolar damage because elevated airway pressure can cause barotrauma to the left lung. Although the oxygenation profiles in our series were acceptable, it might cause significant lung damage and resultant hypoxemia if a patient has underlying lung disorders such as chronic obstructive pulmonary disease or if the procedure under 1-lung ventilation is prolonged. These findings suggest that preoperative risk

assessment is important with special reference to pulmonary comorbidity, and that meticulous anesthetic manipulation is crucial. If we expect the procedure to be prolonged, continuous positive airway pressure to the right lung or intermittent 2-lung ventilation should be applied to avoid irreversible lung damage.

Study Limitations

First, because this was not a prospective randomized study comparing the results between robot-assisted and conventional ThE, it is difficult to define the benefits of robotic assistance over the conventional technique. In regard to the learning curve in robot-assisted ThE, the prone position might also contribute to the acceleration of learning. Second, surgical outcomes may be influenced by the surgeon's prior experience with open esophagectomy or other thoroscopic procedures. Thus, additional robot-assisted ThE series are necessary to confirm the early achievement of comparable proficiency. Third, patient groups were determined only by robot console time. Although robot console time is an important barometer of proficiency, other factors should be considered together in an objective manner. For example, Osugi and colleagues⁴ classified patient groups by logistic analysis of the mean risk of pulmonary complications.

CONCLUSIONS

This study suggests that robotic assistance in the prone position is technically feasible and safe and has the potential to steepen the learning curve of ThE. Prone positioning was well tolerated in our series, but preoperative risk assessment and careful respiratory management should be carried out.

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FIGURE E1. Port placement in the prone position. A 12-mm trocar at the 8th intercostal space for a camera, an 8-mm trocar at the 6th intercostal space medial to the scapular tip (*asterisk*) for a right robotic arm, an 8-mm trocar at the 10th intercostal space for a left robotic arm, and a 12-mm trocar at the 9th intercostal space for an accessory port. C, Camera; R, right robotic arm; L, left robotic arm; A, accessory port.

FIGURE E3. The prone position offers an excellent view of the infra-aortic and left tracheobronchial area. After the infra-aortic nodes were cleared, surgical hemostats were applied to control minor bleeding. A, Aortic arch; B, left main bronchus; C, left lung; D, azygos vein; E, esophagus.

FIGURE E2. Dissection of the upper thoracic esophagus. The esophagus was dissected circumferentially with caution to avoid injury to the trachea or recurrent laryngeal nerve (*arrow*). The high-resolution magnified view, articulation of instruments, and motion scaling can provide easier and more precise dissection at this point. E, Esophagus; T, trachea.