

Aus der Klinik und Poliklinik für Allgemein-, Viszeral- und Transplantationschirurgie
der Universitätsmedizin der Johannes Gutenberg-Universität Mainz

**Implementation of the da Vinci Single-Port robotic system
in the Department of General, Visceral and Transplant Surgery at the University
Hospital of Mainz**

**“Implementierung des da Vinci Single-Port Robotersystems
in der Klinik für Allgemein-, Viszeral- und Transplantationschirurgie der
Universitätsmedizin Mainz”**

Inauguraldissertation
zur Erlangung des Doktorgrades der
Medizin
der Universitätsmedizin
der Johannes Gutenberg-Universität Mainz

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Mainz, 2025

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Tag der Promotion: 03. November 2025

Nachnutzungslizenz: Urheberrechtsschutz (in C-1.0)

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1 Introduction

1.1 History of robotic surgery

While robots aren't new, their application in medicine is quite recent. For example, robotic surgery began 40 years ago, first appearing in fields with stable anatomies such as neurosurgery and orthopedics (1). In 1985, robotic systems were initially employed to precisely manipulate surgical instruments during stereotactic brain biopsies. Subsequently, its application extended to the resection of astrocytomas located in the thalamus (2–4). The integration of robotic systems into visceral surgery occurred over a decade later than in other surgical fields. This delay was primarily due to the mobility of organs, which significantly complicates the use of robotic instruments in these procedures.

In 1995, F. Moll and R. Young established Intuitive Surgical™ and subsequently developed a novel robotic surgical system called MONA®. Two years later, in 1997, Himpens and Cadière utilized the MONA system to perform the first robot-assisted cholecystectomy (5). In 1999, the MONA robotic system was further utilized to perform additional procedures within visceral surgery. Specifically, it was employed for the placement of a gastric band in an obese patient and for the execution of a Nissen fundoplication procedure (6). The MONA system's progress led to the development of the first da Vinci® surgical system. A three-armed robotic prototype was first shown in Europe in January 1999. Over time, the application of this new system gradually expanded to encompass various surgical specialties, including cardiac surgery, colorectal surgery, gynecology, and urology (7–10).

Subsequent enhancements to the da Vinci surgical system resulted in the development of advanced iterations. These include the four-armed da Vinci Xi® and the single-arm da Vinci SP®, the latter specifically designed to facilitate single-incision surgery (Figure 1). The most recent advancement in this series is the da Vinci 5®, which notably incorporates "Force Feedback technology". This innovation enables surgeons to tactilely perceive push and pull forces at the tip of the instrument, providing a new level of sensory input during procedures. The range of operations now achievable with the da Vinci system, along with other emerging robotic systems like the Hinotori™ Surgical Robot System, is extensive and continually expanding.

Figure 1. Da Vinci surgical systems



From the left to the right side: vision cart, da Vinci X® patient-side cart, da Vinci SP patient-side cart, da Vinci Xi patient-side cart, surgeon console (Intuitive Surgical™).

1.2 Evolution of the surgical treatment of esophageal cancer

Based on the Global Cancer Statistics 2020 data, esophageal cancer ranks as the seventh most common cancer in terms of incidence, with an estimated 604,000 new cases annually. It also holds the sixth position for overall cancer mortality, accounting for approximately 544,000 deaths per year. A notable sex-based disparity exists, with men exhibiting incidence and mortality rates 2 to 3 times higher than women, comprising roughly 70% of all cases. Geographically, Eastern Asia reports the highest regional incidence rates for both men and women, largely influenced by the significant burden in China. This is followed by Southern Africa, Eastern Africa, Northern Europe, and South Central Asia (Figure 2) (11).

Esophagectomy, while being the primary treatment for esophageal cancer, is recognized as a highly invasive and technically demanding surgical procedure. Its complexity often stems from the potential requirement for multiple surgical access points (e.g., abdominal, thoracic, and cervical), alongside the need for advanced surgical technical skills (12). In 1913, Franz John A. Torek achieved the first successful transthoracic resection for esophageal cancer. He used an external rubber tube, stretching from the upper esophagus to the stomach, for the reconstruction. Remarkably, the patient survived this procedure for 12 years (13). In 1946, Ivor Lewis introduced a two-stage transthoracic esophagectomy. This procedure involved initial gastric mobilization, followed two weeks later by the esophageal resection and reconstruction via a right thoracotomy (14). In 1976, McKeown introduced a different way to perform an esophagectomy, using three separate incisions. This method commences with a right thoracotomy as the initial stage. Subsequently, the patient is repositioned into the supine position to facilitate an abdominal incision and, typically, a left cervical incision, through which a cervical esophagogastric anastomosis is performed (15). In 1978, Orringer and Sloan were

the first to publish their experiences with a series of blunt transhiatal esophagectomies. This particular operation could be a suitable option for patients who are unable to undergo a thoracotomy. Potential benefits of the transhiatal approach include a reduction in postoperative pain and a lower incidence of certain postoperative complications, such as pneumonia and mediastinitis (16).

In 1992, Minimally invasive transthoracic esophagectomy (MIE) was initially reported by Cuschieri et al., marking the first description of thoracoscopic esophagectomy (17). The TIME trial, published in *The Lancet* in 2012, represents the first randomized controlled trial (RCT) to compare MIE with open esophagectomy (18). This multicenter European study randomized 115 patients to undergo either MIE or open esophagectomy. The primary endpoint evaluated was the incidence of in-hospital pulmonary infection within two weeks post-surgery. While both Ivor Lewis and McKeown procedures were performed, the three-incision McKeown technique was the more frequently chosen option for patients. The study findings demonstrated a significantly lower rate of pulmonary infectious complications following MIE compared to open esophagectomy, both within two weeks and during the entire hospital stay. Furthermore, MIE led to less bleeding, quicker discharges from the hospital, and a better quality of life. Conversely, the open group experienced shorter operation times but a higher incidence of vocal cord paralyses (19,20).

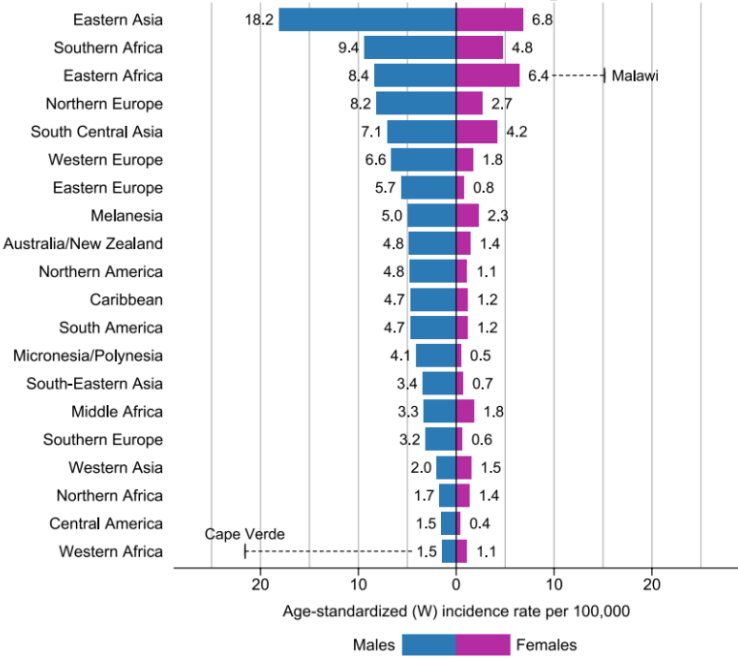
While MIE offers considerable benefits over open esophagectomy, leading to its widespread adoption in Europe, it presents unique challenges. The esophagus's proximity to vital structures like the aorta, heart, and airway necessitates an exceptionally delicate dissection. Furthermore, constructing an intrathoracic anastomosis is a technically demanding maneuver that requires a lengthy learning curve. The current reliance on rigid instruments also limits the full potential of the minimally invasive approach in esophageal surgery.

The application of a robotic system presents an option to address several challenges associated with MIE. Robot-assisted MIE (RAMIE) was first introduced in 2005. Since then, long-term studies have confirmed that it's both feasible and safe (21,22). The robotic system offers notable technical benefits compared to traditional minimally invasive surgery, primarily by improving visualization and making instrument manipulation easier. Surgeons benefit from a full 3D image of the operative field, projected directly in line with their normal working axis via a console. From this console, the surgeon controls two joysticks, with their movements precisely translated to the robotic arms.

The robotic instruments offer expanded capabilities, including additional degrees of freedom of motion (articulated wrists) and the ability to scale and filter the surgeon's movements, effectively eliminating tremor. This enhanced dexterity and precision can be particularly beneficial in areas challenging to access with conventional instruments. Outcomes of MIE and RAMIE were compared in several RCTs. For example, the ROBOT trial, a single-center

randomized controlled study, involved 112 patients. Participants were randomly assigned to receive either RAMIE or open esophagectomy. (23). The study's main objective was to assess the frequency of overall surgery-related postoperative complications, which occurred less often in the RAMIE group compared to the open esophagectomy group. Patients who underwent RAMIE experienced fewer pulmonary complications and cardiac complications compared to those receiving open esophagectomy. RAMIE also demonstrated several other benefits, such as less postoperative pain, improved functional recovery by postoperative day 14 and higher quality of life scores at hospital discharge. The RAMIE trial, another prominent RCT, was a Chinese multicenter study designed to assess the effectiveness and safety of RAMIE in comparison to MIE for the treatment of resectable esophageal squamous cell carcinoma (SCC) (24). RAMIE procedures were significantly faster than MIE. For patients who received neoadjuvant therapy, RAMIE also led to a greater number of thoracic lymph nodes being removed. Additionally, the success rate for dissecting lymph nodes along the left recurrent laryngeal nerve was higher with RAMIE. The REVATE trial was an Asian multicenter randomized clinical trial designed to compare the efficacy and safety of RAMIE against MIE specifically for the dissection of lymph nodes located along the left recurrent laryngeal nerve (RLN) (25). Patients diagnosed with esophageal SCC were randomly assigned to undergo either minimally invasive or robotic McKeown esophagectomy. The study primarily aimed to ascertain the success rate of left RLN lymph node dissection, defined by the removal of at least one lymph node without permanent nerve damage (lasting over six months). Successful left RLN lymph node dissection was considerably more frequent in the RAMIE group than in the MIE group. Additionally, RAMIE patients had less left recurrent laryngeal nerve palsy (RLNP) one week and six months post-surgery. More mediastinal lymph nodes were removed in the RAMIE group. In European settings, a direct comparison between RAMIE and MIE was made in the Robot-2 Trial, which results are still highly anticipated (26). In this multicenter randomized superiority trial, 218 patients with resectable esophageal adenocarcinoma (ADC) of the intrathoracic esophagus or ADC of the gastroesophageal junction are randomized to either RAMIE or MIE. This study's main goal is to count the total number of abdominal and mediastinal lymph nodes removed, categorized by their specific lymph node station. The results of this study could potentially settle the difference between these two approaches in the treatment of esophageal cancer.

Figure 2. Esophageal cancer age-standardized incidence rates by sex in 2020.



The highest national rates for men and women are overlaid, and rates are presented in descending order of the age-standardized rate for men around the world (Globocan 2020).

1.3 Minimally invasive transcervical esophagectomy

In 2015, Fujiwara et al. were the first to describe a single-port mediastinoscopic technique for dissecting the upper mediastinum during esophageal cancer surgery (27). The technique involved accessing the mediastinum through a left cervical incision. A wound seal protector was then utilized to inflate the mediastinal space with carbon dioxide. This created a capnopneumomediastinum, which expanded the area and improved visibility of tiny structures around the aortic arch in the upper mediastinum, like nerves, bronchial arteries, and lymphatic vessels. This enhanced view could potentially lead to safer and more thorough lymphadenectomies. However, achieving a systematic lymph node dissection in the upper mediastinum remains difficult due to the confined surgical space and limitations in instrument movement. Robotic systems offer a way to alleviate these issues, as they reduce robotic arm collisions and shorten operating times, which is a crucial factor in preventing complications after surgery. Unlike MIE, which require one-lung ventilation, the Minimally invasive transcervical esophagectomy (MICE) procedure accesses the middle and upper esophagus from the neck, thereby eliminating the need for chest wall incisions and one-lung ventilation (28). Since there aren't enough comprehensive literature reviews or randomized trials directly comparing MIE and MICE, it's impossible to definitively conclude how effective this promising technique is in terms of surgical completeness and patient recovery. Nevertheless, MICE still

stands as a valid choice for individuals who are unable to undergo thoracotomy or thoracoscopic surgery.

1.4 Robot-assisted cervical esophagectomy

A variety of studies affirmed the feasibility and safety of MICE, showing favorable short-term postoperative and oncologic outcomes (29–31). Still, performing a transcervical mediastinoscopic dissection comes with technical hurdles, much like those in single-port laparoscopic surgery. These difficulties stem from needing all instruments to work in the same direction within a tight area. Robot-assisted cervical esophagectomy (RACE) might help overcome these limitations (32). The initial documentation of RACE appeared in 2016. Mori et al. published this first report, demonstrating the technique using a cadaveric model and the da Vinci Xi surgical system (33). In 2019, Grimminger et al. and Chiu et al. moved the field forward. They performed the first fully robotic transcervical mediastinoscopic dissections for esophagectomy in cadaveric models, utilizing the da Vinci SP surgical system (34,35). That same year, in 2019, Egberts et al. and Nakauchi et al. published the first clinical series of RACE procedures performed on patients, which helped establish this new approach's initial safety (36,37). Expanding on these advancements, Fujita et al. in 2024 demonstrated the feasibility of RACE when utilizing a bilateral cervical approach - a modification of a technique initially outlined by Daiko et al. for MICE (38,39). The same group also studied the operation duration when the abdominal and transcervical steps were done at the same time versus one after another (simultaneous versus sequential approach). They found that doing these parts concurrently significantly cut down the overall operation time (40). The da Vinci SP system's recent emergence in Europe and beyond has profoundly reimagined surgical approaches, providing surgeons with advanced methods for treating esophageal cancer (41,42).

1.5 Implementation of the da Vinci SP system at the University Hospital of Mainz

The da Vinci SP system was introduced to the Department of General, Visceral and Transplant Surgery at the University Hospital of Mainz in April 2024. For the first time in Europe, the da Vinci SP system has been implemented in the clinical practice of an upper gastrointestinal (GI) center for esophagectomies. This innovative robotic system allows for the use of a single small incision or entry through a natural body opening, providing a minimally invasive option for complex procedures. The SP system allows for a wide range of surgical procedures, especially in GI surgery.

Historically, robot-assisted esophageal procedures have relied on either transhiatal or transthoracic approaches. However, advancements in robotic technology - exemplified by the da Vinci SP system - may now allow for more precise access to the esophagus through a single-port incision. Consequently, new techniques to approach esophagectomy are emerging. Regarding the cervical access for procedures like cervical anastomosis or three-field lymphadenectomy, open surgery is traditionally the most used approach and the use in minimally invasive esophageal surgery has been limited, especially in the Western world. However, the introduction of the da Vinci SP system enables in this context controlled transcervical mediastinoscopic dissection. The Single-port Robotic-Assisted Cervical Esophagectomy (SP RACE) procedure employs a laparoscopic approach combined with transcervical mediastinoscopic dissection. This procedure was performed with the use of the da Vinci SP system for the first time worldwide at the University Hospital of Mainz (41). It circumvents the need for single lung ventilation or thoracic access and expands surgical options for patients with significant comorbidities.

Another innovative approach is represented by the Single-Port Subcostal Robotic-Assisted Minimally Invasive Esophagectomy (SP SC RAMIE), which combines laparoscopy with subcostal mediastinal dissection. This procedure was first performed in Europe at the University Hospital of Mainz (42). It avoids the need of thoracotomy, reducing postoperative pain and speeding the recovery process.

1.6 Aim of the dissertation

This work aims to describe the different types of procedures currently performed by Professor P. P. Grimminger and our team at the University Hospital of Mainz. The range of techniques spans from simple cholecystectomies to more technically complex esophagectomies, which will be the focus of this dissertation.

The first worldwide series of SP RACE procedures will be analyzed.

Furthermore, the literature background of SP RACE will be researched through a systematic literature review and meta-analyses, aiming to evaluate how technological advancements in the field of robotic surgery have significantly improved the treatment of patients with esophageal cancer.

2 Procedures

2.1 SP RACE

The SP RACE involves two phases: the abdominal phase is normally performed laparoscopically but could be performed robotically using both the da Vinci SP and Xi Systems. The technical details of this phase were already described previously in different articles (43,44). The second phase is the transcervical mediastinoscopic dissection and it involves the use of the da Vinci SP system (41). These two phases can be performed simultaneously or sequentially.

2.1.1 Abdominal phase

During the abdominal phase, the patient is positioned in a French and anti-Trendelenburg position. The placement and sizes of the abdominal trocars are shown in Figure 3. A laparoscopic CO₂ pressure of 15 mmHg is used. The left lobe of the liver is elevated with a 5 mm liver retractor inserted through the right 5 mm trocar, which is fixed with a Martin arm. The camera is introduced through the umbilical 12 mm trocar. The hiatus is dissected. The greater curvature is dissected beginning from the corpus region beyond the epiploic vessels and extending toward the left crus of the diaphragm; in this area, a portion of the greater omentum is preserved just below the spleen for a later omentum wrap covering the anastomosis. At the level of the Crowfoot, the vessels are sealed and the stomach is dissected in the Crowfoot region, where an Endo GIA 60 mm violet stapler cartridge is used to make the first incision for the subsequent gastric sleeve. The stapler is inserted through the 12 mm trocar. The conduit is then formed using up to seven 60 mm violet stapler cartridges, aiming for a width of 4 to 5 cm. The gastric fundus is completely transected, and the conduit fully formed. Stay sutures are placed to hold the small curvature and the tip of the conduit together, ensuring a less robust specimen for easy removal transmediastinally and transcervically. Following the formation of the conduit, the lymph nodes along the hepatic, left gastric, and splenic arteries are dissected.

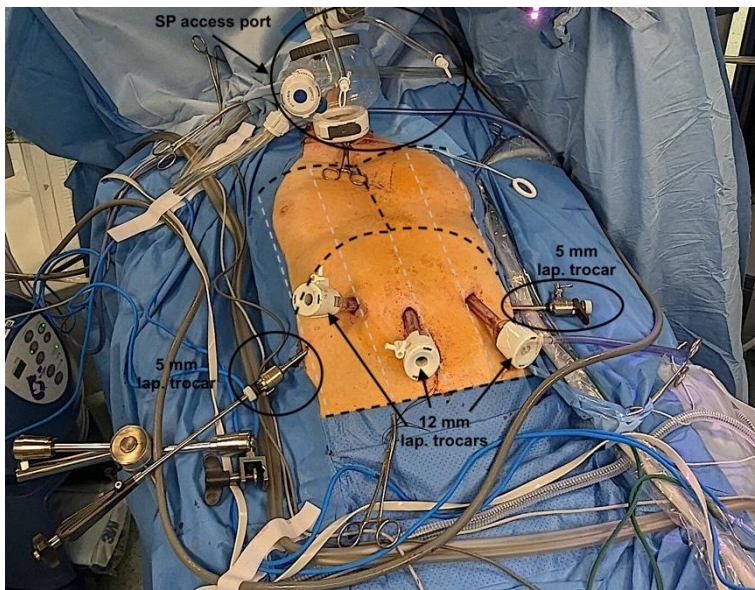
2.1.2 Transcervical mediastinoscopic dissection

The transcervical mediastinal dissection commences with a 3-cm transverse skin incision, precisely positioned approximately two fingerbreadths superior to the left clavicle and anteromedial to the sternocleidomastoid muscle. The platysma and strap muscles are subsequently transected. Lateral displacement of the left sternocleidomastoid muscle, transection of the caudal thyroid vessels, and medial displacement of the inferior thyroid pole provide crucial exposure. The left RLN is then meticulously identified and its functional integrity

confirmed via neuromonitoring. Following this, the left common carotid artery is carefully dissected from its surrounding tissues medially until the left aspect of the esophagus is fully visualized. Once the esophagus is adequately mobilized, a sling is positioned around it to facilitate retraction for the subsequent upper mediastinal preparation. Immediately thereafter, a large SP access port is introduced, and 8 mmHg of pressure is applied to induce capnopneumomediastinum (Figure 3). To optimize the restricted surgical field, a high-flow insufflator is employed, ensuring consistent working space. The da Vinci SP patient cart is positioned on the patient's right side, allowing the robot to be connected. Subsequently, the left tracheal wall is exposed and retracted to the right to aid in identifying the left RLN, a critical step guided by continuous neuromonitoring. Dissection then proceeds along the left RLN to free the upper mediastinal esophagus and its associated lymph nodes (Figure 4). Utilizing Maryland bipolar forceps, the esophagus is meticulously separated from the trachea, with the spinal vertebrae serving as definitive dorsal and lateral anatomical reference points for mediastinal dissection. Adherence to these planes ensures precise delineation of the parietal pleura, which then acts as a crucial boundary for further dissection. The aortic arch is identified in conjunction with the left RLN, with its integrity validated by neuromonitoring. Subsequently, circumferential dissection of the esophagus and periesophageal lymph nodes is performed, guided by the azygos vein and descending aorta as critical anatomical references. At this juncture, indocyanine green (ICG) dye, previously administered during the abdominal phase, can be invaluable for visualizing and preserving the thoracic duct (Figure 5). Simultaneous dorsal and superior retraction of the esophagus allows for meticulous caudal tracing of the trachea to the carina. Here, the right and left main bronchi and the carina itself are identified and precisely dissected free from the esophagus, taking utmost care to prevent iatrogenic injury. Transcervical access significantly facilitates comprehensive carinal lymph node dissection. At the subcarinal level and distally, the ventrally positioned pericardium and the bilateral parietal pleura serve as key anatomical guides as the esophagus is meticulously liberated towards the hiatus.

Esophageal reconstruction commences immediately following the completion of the esophageal resection, which is finalized laparoscopically at the hiatus. Upon undocking the robotic system, the resected specimen is retrieved. For transmediastinal specimen extraction, the gastric fundus is completely transected during the abdominal phase, and the gastric conduit fully formed. Stay sutures are strategically placed to appose the lesser curvature and the conduit tip, creating a less bulky specimen for facile transmediastinal and transcervical extraction using a laparoscopic grasping instrument. This maneuver is executed during a controlled apneic phase induced by the anesthesiologist. Subsequently, an end-to-side stapled esophagogastrostomy is fashioned utilizing a 25-mm circular stapler. Postoperatively, drains are typically not employed, and the procedure is concluded with standard skin closure.

Figure 3. SP RACE port and trocars placement.



During the abdominal phase the following trocars are utilized:

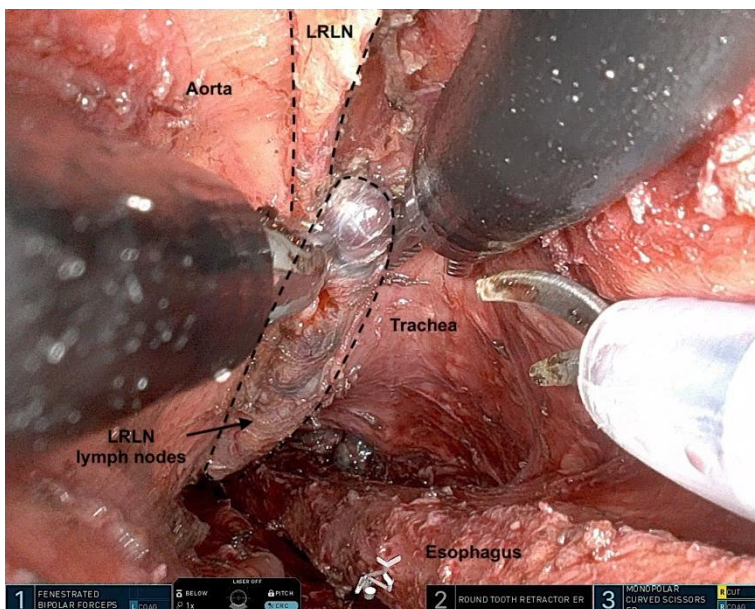
One 12mm optic trocar supraumbilical,

two 12 mm trocars in the midclavicular lines left and right,

two 5mm trocars in the subcostal lines left and right.

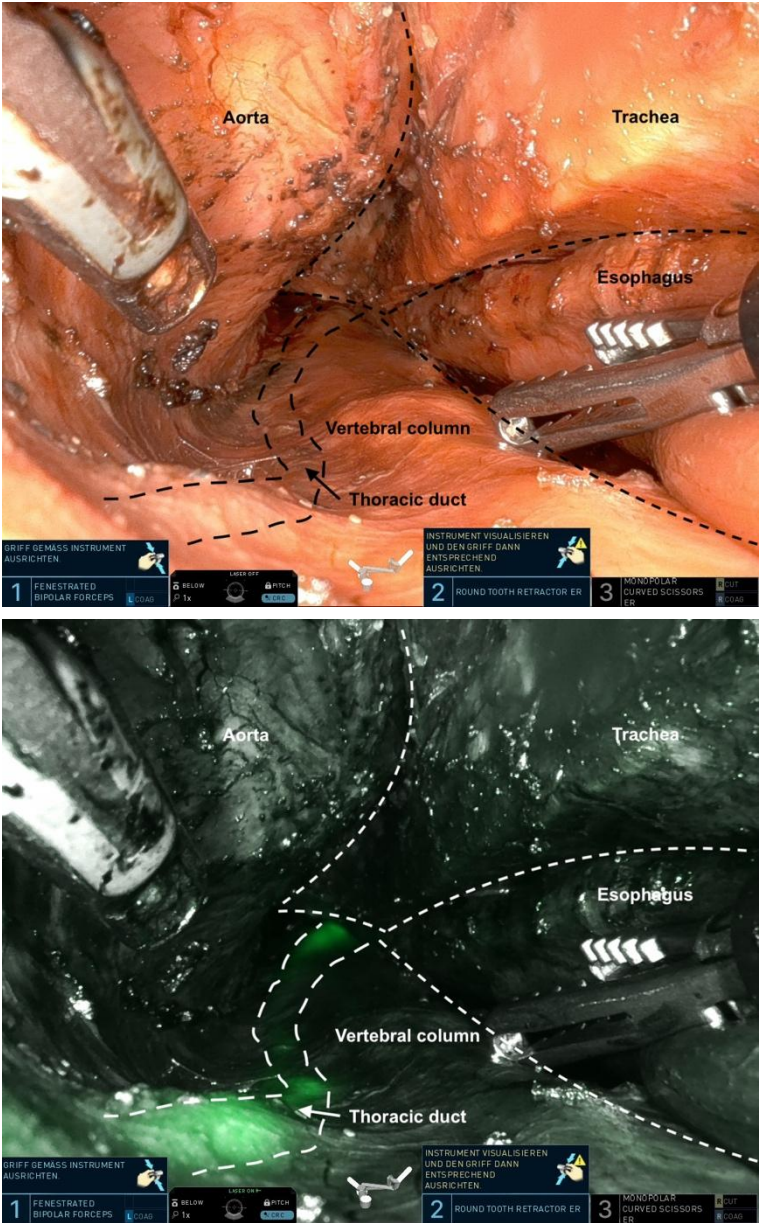
After incision above the left clavicle and anteromedially to the left sternocleidomastoid muscle, a large incision (2.7 cm) single-port access port is inserted and a pressure of 8 mmHg is applied to induce capnopneumomediastinum. This step is fundamental to begin the transcervical mediastinoscopic dissection.

Figure 4. Dissection of the lymph nodes along the LRLN.



LRLN: left recurrent laryngeal nerve.

Figure 5. Thoracic duct visualization under Firefly™ mode.



Top: the descending aorta serve as crucial landmarks during the circumferential dissection of the esophagus and paraesophageal lymph nodes.

Bottom: indocyanine green (ICG) dye is used to visualize and spare the thoracic duct.

2.2 SP SC RAMIE

The Single-Port Subcostal Robotic-Assisted Minimally Invasive Esophagectomy (SP SC RAMIE) involves two phases. The abdominal phase is normally performed laparoscopically but could be performed robotically using both the da Vinci SP and Xi Systems (Intuitive Surgical Inc.). The technical details of this phase were already described previously in different articles (43,44). The second phase is the subcostal mediastinal dissection and it involves the use of the da Vinci SP system.

2.2.1 Abdominal phase

During the abdominal phase, the patient is positioned in a French and anti-Trendelenburg position. The placement and sizes of the abdominal trocars were already described for the SP RACE procedure (Fig. 3). A laparoscopic CO₂ pressure of 15 mm Hg is used. The left lobe of the liver is elevated with a 5 mm liver retractor inserted through the right 5 mm trocar, which is fixed with a Martin arm. The camera is introduced through the umbilical 12 mm trocar. The hiatus is dissected. The greater curvature is dissected beginning from the corpus region beyond the epiploic vessels and extending toward the left crus of the diaphragm; in this area, a portion of the greater omentum is preserved just below the spleen for a later omental wrap covering the anastomosis. At the level of the Crowfoot, the vessels are sealed and the stomach is dissected in the Crowfoot region, where an Endo GIA 60 mm violet stapler cartridge is used to make the first incision for the subsequent gastric sleeve. The stapler is inserted through the 12 mm trocar. The conduit is then formed using up to four 60 mm violet stapler cartridges, aiming for a width of 4 to 5 cm. The gastric sleeve preparation is not fully completed for a greater variability in choosing the best gastric anastomosis region later. Following the formation of the conduit, the lymph nodes along the hepatic, left gastric, and splenic arteries are dissected. The lymph nodes of the lower mediastinum are also dissected with a transhiatal approach and the right pleura is open. The opening of the pleura ensures a safe trocars placement during the thoracic phase.

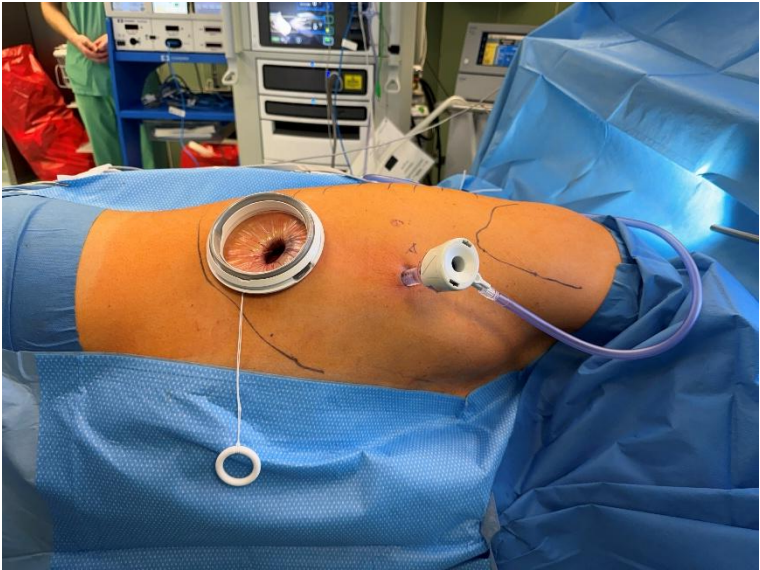
2.2.2 Subcostal mediastinal dissection

For the subcostal mediastinal dissection, the patient is first moved from a left lateral to a semi-prone position. A thoracoscopy is initiated by inserting a 12 mm optic trocar through the seventh intercostal space. Next, a 4 cm subcostal incision is created at the posterior axillary line, allowing careful entry into the thoracic cavity while meticulously avoiding damage to the diaphragm. Stay sutures are then placed to secure the diaphragm to the fascia. A large SP access port is inserted, and a pressure of 7 mmHg is applied to induce a capnopneumothorax

(Figure 6). The da Vinci SP patient-side cart is positioned on the patient's right, and the robot is then docked. Once the lung has collapsed and the pulmonary ligament and pleura are divided, the pleura is separated from the pericardium, moving towards the right main bronchus and along the azygos vein. If ICG was administered into the mesenteries during the abdominal phase, the thoracic duct can be visualized and preserved using Firefly™ mode (Figure 7). The aorta is then exposed along the azygos vein, traced down to the hiatus. At this point, the left pleura is dissected from the pericardium. The esophagus is subsequently tunneled under, and the periesophageal lymph nodes are dissected en-bloc. Care is taken to preserve the bronchial branches of the right vagal nerve and the right bronchial artery. The lymph nodes at the tracheal bifurcation are completely dissected and left with the specimen (Figure 8). The skeletonized esophagus is then divided with scissors at the carinal level, and a purse-string suture is placed in the esophageal stump.

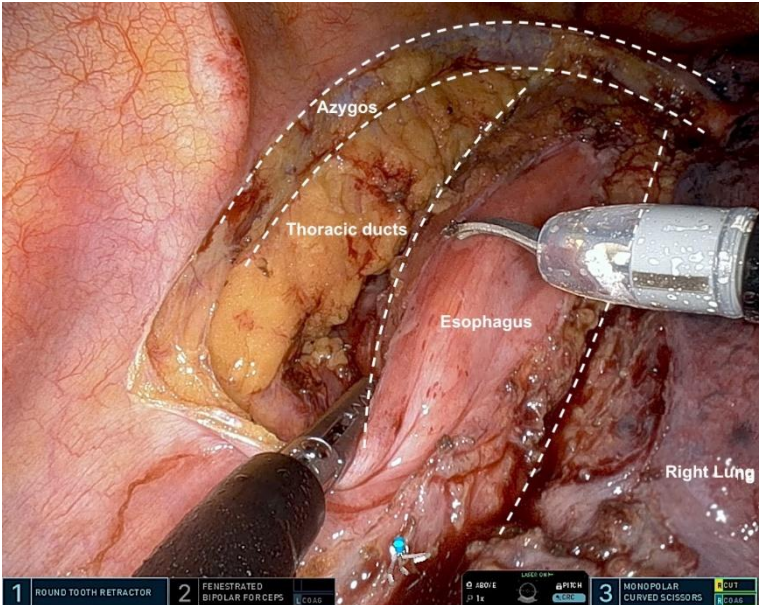
The reconstruction phase begins after the robot is undocked and the specimen is resected. The anvil of a circular stapler is inserted into the esophageal stump through the subcostal approach (Figure 9). The purse-string suture is tied externally. The prepared gastric tube, still connected to the resected specimen by a bridge of unresected stomach fundus, is then fully advanced into the chest cavity. The specimen is subsequently externalized through the subcostal incision. Following this, the stapler is introduced into the gastric tube at the chosen location after a gastrotomy, allowing for the creation of an end-to-side stapled esophagogastrostomy to the posterior gastric wall. The remaining portion of the stomach is then resected using an Endo GIA stapler, and the specimen is removed. The robot is then redocked to create an omental flap, which is meticulously covered by the previously formed pleural tent. Once the robot is undocked, a thoracic drain is placed via the assistant trocar, marking the completion of the procedure with skin sutures.

Figure 6. Subcostal mediastinal dissection.



*Large SP access port in subcostal position.
One 12 mm optic in the 7th intercostal space.*

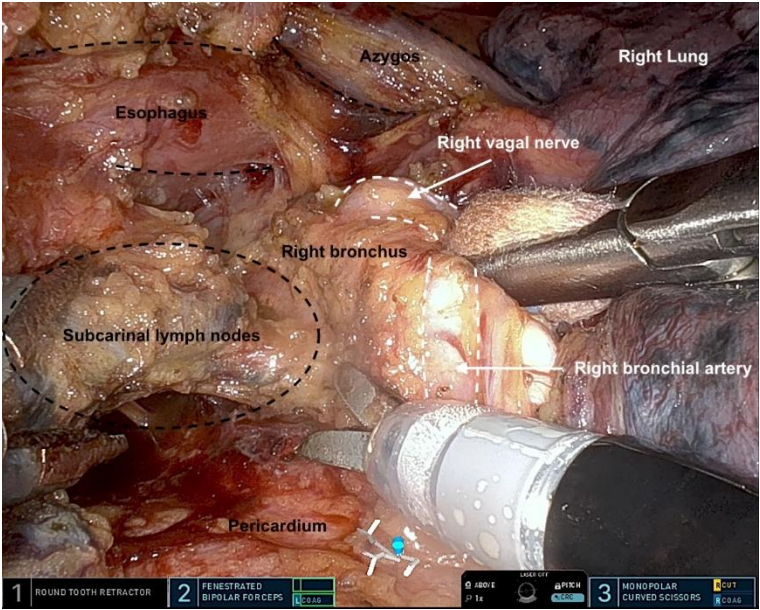
Figure 7. Thoracic duct visualization under Firefly™ mode.



Top: The pleura is separated along the azygos vein preserving the thoracic duct - Firefly™ mode.

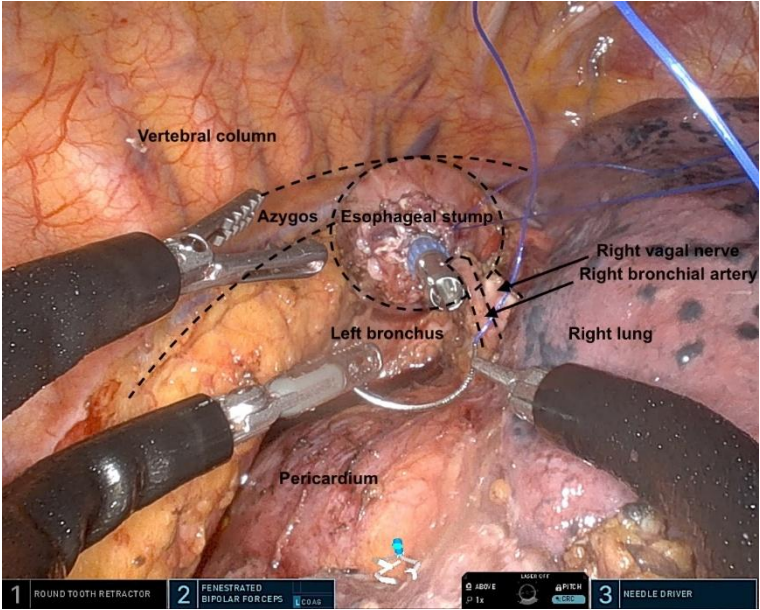
Bottom: The pleura is separated along the azygos vein preserving the thoracic duct – normal vision.

Figure 8. Subcarinal lymph nodes dissection.



The esophagus is tunneled underneath and the subcarinal lymph nodes are dissected.

Figure 9. The anvil of a circular stapler (Covidien, USA) is inserted into the esophageal stump.



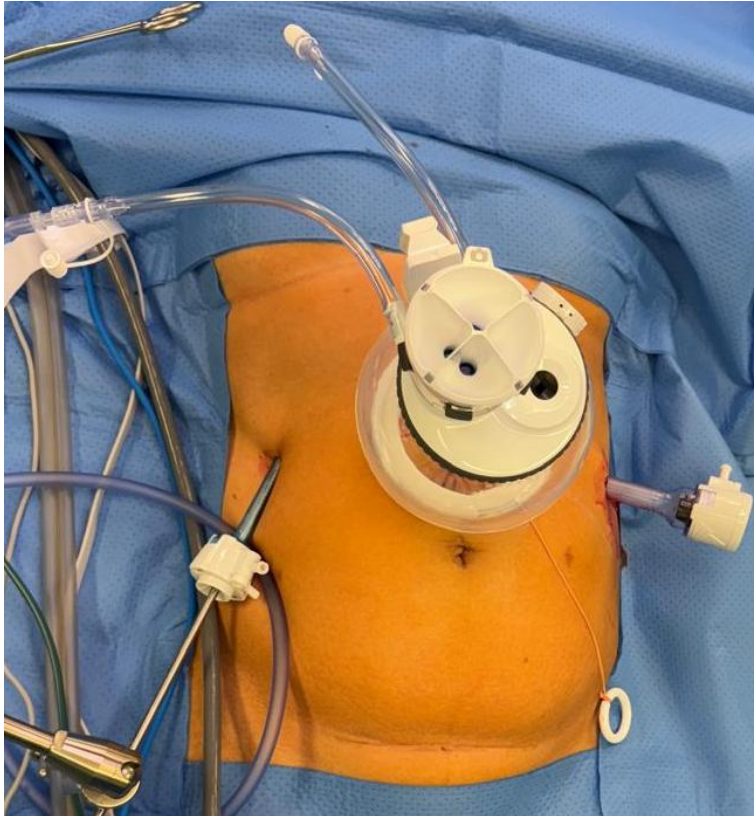
The anvil of a circular stapler is inserted into the esophageal stump.

2.3 SP gastrectomy

The procedure is performed with the patient in a supine and anti-Trendelenburg position. A short stab incision is made in the left mid-abdomen, approximately one hand-width lateral to the umbilicus, followed by the insertion of a Veress needle to establish pneumoperitoneum. A 12-mm trocar is then placed, and a diagnostic laparoscopy is performed to assess the surgical field. Under direct visualization, the additional trocars are placed: a 5-mm trocar in the right subcostal region for the liver retractor, and a 3-cm minilaparotomy for the Access Port Large (Figure 10). The da Vinci SP system is subsequently docked. The left lobe of the liver is elevated using a liver paddle, which is secured to the Martin arm. The procedure begins with the division of the lesser omentum using the Bipolar Maryland forceps (Forced Triad) and scissors, with partial assistance from the assistant trocar using LigaSure. Circumferential dissection of the hiatus is performed, ensuring that the paracardial lymph nodes remain attached to the esophagus. The gastrosplenic ligament is divided outside the vascular arcade of the greater curvature using bipolar forceps and scissors, and the dissection proceeds towards the gastrocolic ligament. The greater omentum is completely detached from the transverse colon, allowing for the mobilization of the right colonic flexure, with any adhesions carefully released. The right gastroepiploic artery and vein are dissected, clipped, and divided. The lymph node station 6 is fully dissected and remains attached to the specimen (Figure 11). The lymph nodes are traced proximally and divided at the antrum-corpus junction after clip application. The lesser curvature of the stomach is then mobilized, ensuring the complete removal of all associated lymph nodes. Further dissection includes a detailed lymphadenectomy of stations 8 and 12, along the hepatoduodenal ligament. The right gastric vessels are clipped and divided. The dissection then continues along the superior border of the pancreas, with lymphadenectomy extending along the proper and common hepatic arteries, the portal vein, and the splenic artery, including the splenic hilum (station 10). The left gastric vein is clipped and divided with scissors. The lymph nodes of station 9 are dissected, followed by station 7, which is carefully prepared at the origin of the left gastric artery, ensuring that the lymphatic tissue remains attached to the artery towards the stomach. The left gastric artery is clipped proximally and peripherally with Hem-o-lok, then divided with scissors (Figure 12). The diaphragmatic crura are dissected, and the retroperitoneal adhesions of the gastric fundus are released. The post-pyloric duodenum and the stomach at the cardia are transected using two charges of a 60-mm Endo GIA stapler (purple cartridge). The specimen is retrieved via the minilaparotomy of the SP Access Port. The reconstruction phase begins with the preparation of the jejunum. The jejunum is transected approximately 30 cm distal to the ligament of Treitz, and a jejunal loop is formed with ligation of individual vessels. An end-to-side jejunojejunostomy is performed, followed by

the retrocolic transposition of the jejunum into the upper abdomen. A side-to-side esophagojejunostomy is created using a 45-mm EndoGIA stapler (purple cartridge), followed by hand-sewn reinforcement using the da Vinci SP and V-Loc sutures. A continuous suture technique is applied using V-Loc sutures.

Figure 10. Port placement for RAMIG



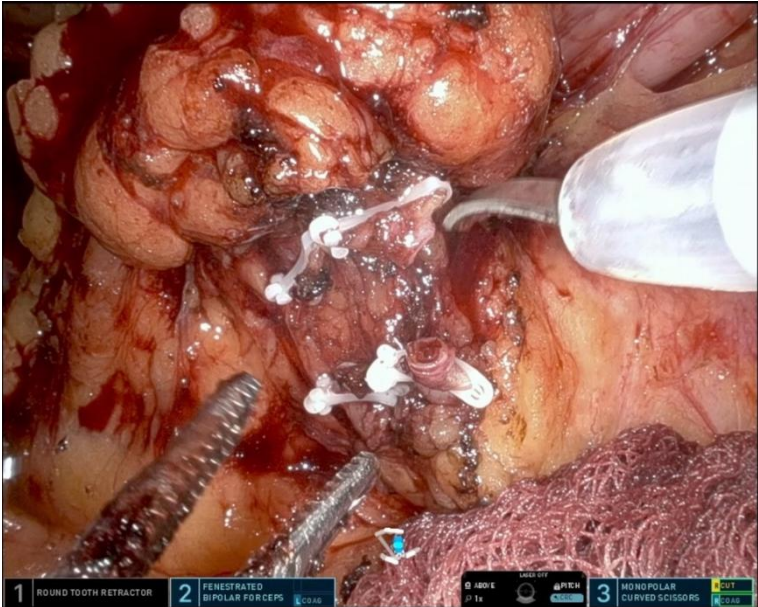
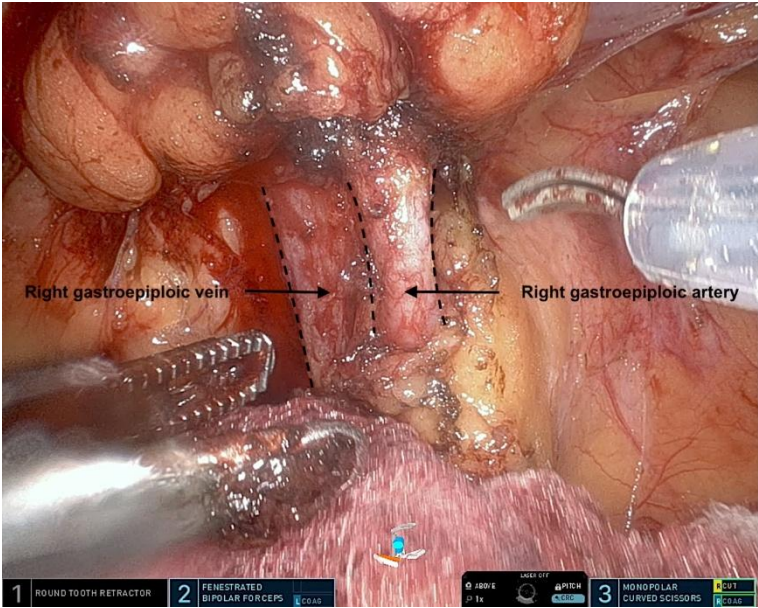
Access-Port Large in supraumbilical midline.

One 5-mm trocar in the right subcostal region

One 12-mm trocar in the left mid-abdomen at the midclavicular line.

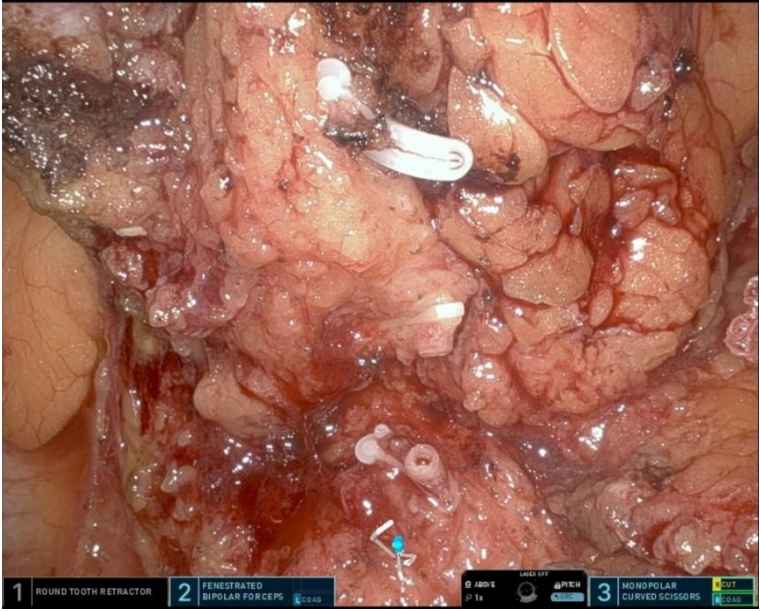
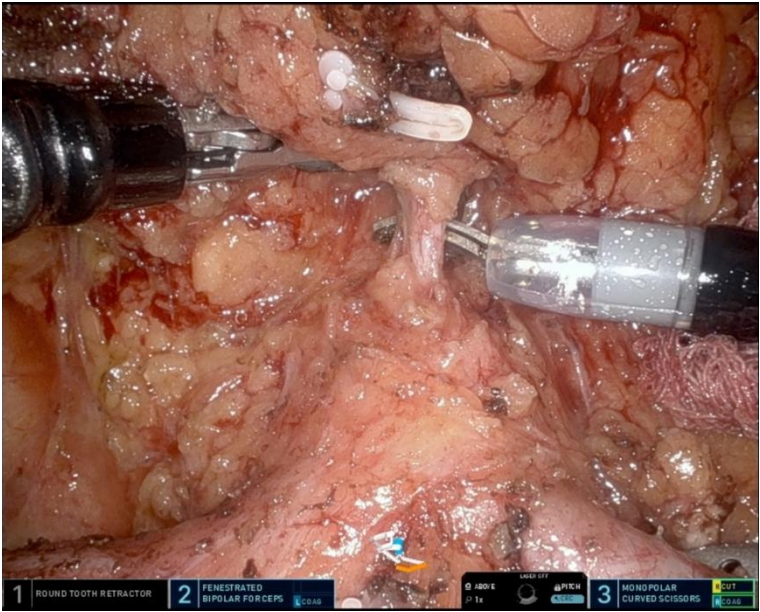
In toupet fundoplication the disposition is the same, but instead of an Access-Port Large, an Access-Port Mini will be utilized, and instead of a 12-mm trocar a second 5 mm trocar will be inserted..

Figure 11. Right gastroepiploic vessels



Top picture: Right gastroepiploic vein and artery
Bottom picture: Clipped and dissected vessels

Figure 12. Left gastric artery



Top picture: left gastric artery

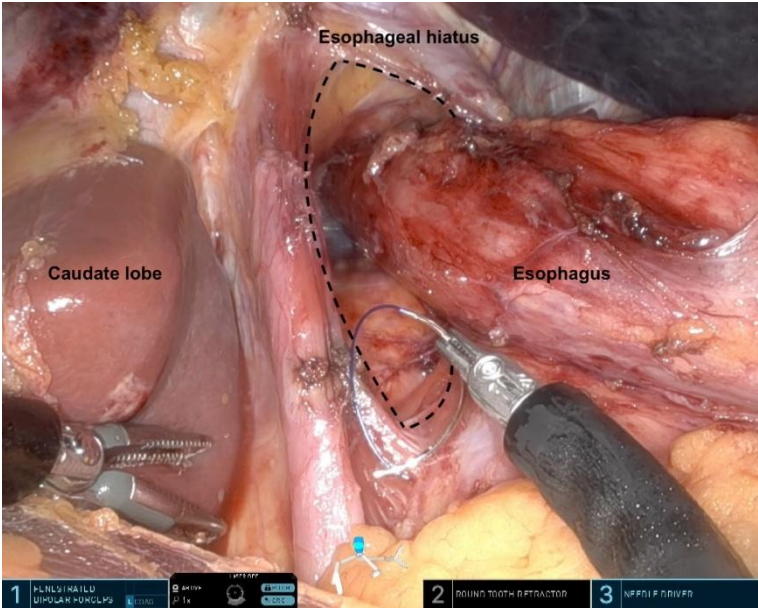
Bottom picture: clipped and severed vessel

2.4 SP fundoplication

The procedure is performed with the patient in a supine and anti-Trendelenburg position. A supraumbilical midline incision is made, followed by entry into the abdominal cavity and the placement of the Access-Port Mini. A pneumoperitoneum is established, after which the da Vinci SP system is docked. An initial inspection of the surgical field is performed. Under direct vision, the additional trocars are inserted: a 5-mm trocar in the right subcostal region and a 5-mm trocar in the left mid-abdomen at the midclavicular line. A liver paddle is introduced through the right 5-mm trocar and secured to the Martin arm (Figure 10). The gastroesophageal junction is exposed, and the hepatogastric ligament is opened using the Maryland bipolar forceps. Dissection of the gastroesophageal junction is performed by opening the peritoneum and exposing the right diaphragmatic crus. The dorsal mediastinum is carefully dissected, ensuring preservation of the vagal nerve. Circumferential mobilization of the distal esophagus is achieved.

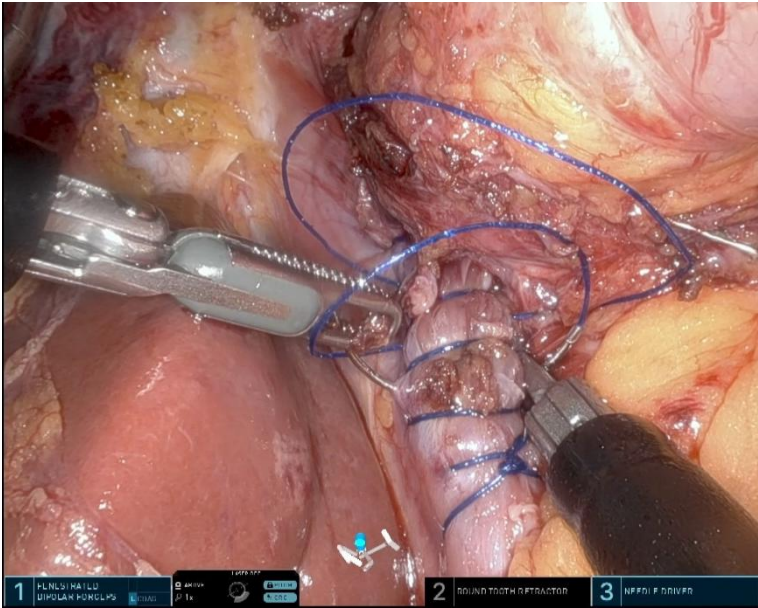
The greater curvature of the stomach is then skeletonized by dividing the short gastric vessels using bipolar and Maryland bipolar forceps. Once the distal esophagus is fully mobilized, it can be encircled bluntly and laterally exposed with forceps. Further mediastinal dissection is performed, allowing for complete mobilization of the lower esophagus into the abdomen (Figure 13). With a gastric tube in place, a posterior hiatoplasty is performed using a continuous suture (Figure 14). Subsequently, a fundoplication wrap is created, ensuring adequate formation of the fundoplication. A 270° Toupet fundoplication is then completed using a total of five sutures, with one suture securing the fundus to the diaphragmatic crura (Figure 15). The gastric tube is removed under direct vision, and the fundoplication wrap is assessed using forceps, ensuring that it remains loosely passable underneath.

Figure 13. Complete mobilization of the lower esophagus.



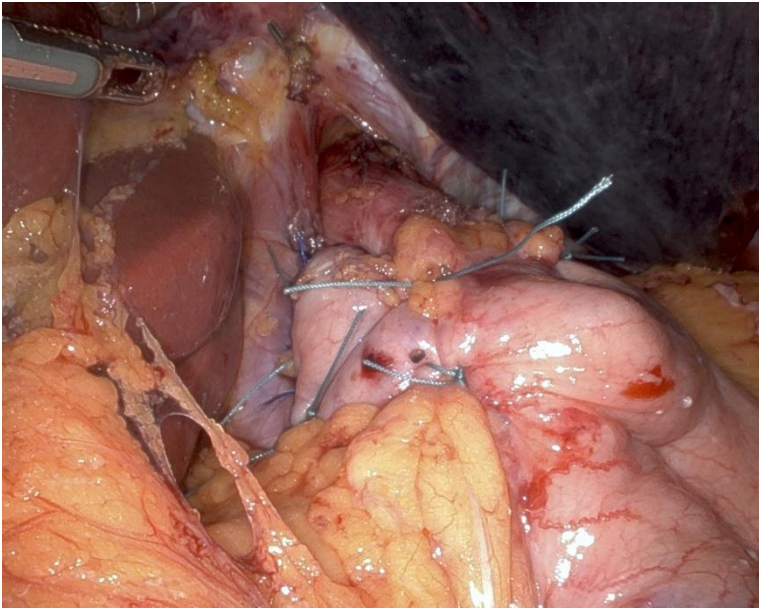
Complete mobilization of the lower esophagus into the abdomen.

Figure 14. Hiatoptasty.



Performing the posterior hiatoptasty using a continuous suture.

Figure 15. 270° Toupet fundoplication.



Complete 270° Toupet fundoplication with one suture securing the fundus to the diaphragmatic crura.

2.5 SP cholecystectomy

The procedure is performed with the patient in a supine and anti-Trendelenburg position. The SP trocar is introduced through the umbilicus and capnopneumoperitoneum induced. The da Vinci SP system is docked, and the camera introduced (Figure 16). An initial inspection of the surgical field is performed, and the instruments are introduced. The gallbladder is grasped and elevated over the liver margin. The peritoneum over the gallbladder infundibulum is incised bilaterally using scissors, exposing Calot's triangle. After clear identification of the cystic duct and cystic artery, both structures are divided between clips without complications (Figure 17). The gallbladder is then dissected in a retrograde fashion from the gallbladder bed. Once fully mobilized, the gallbladder is placed in a retrieval bag and extracted. A hemostatic check confirms adequate bleeding control.

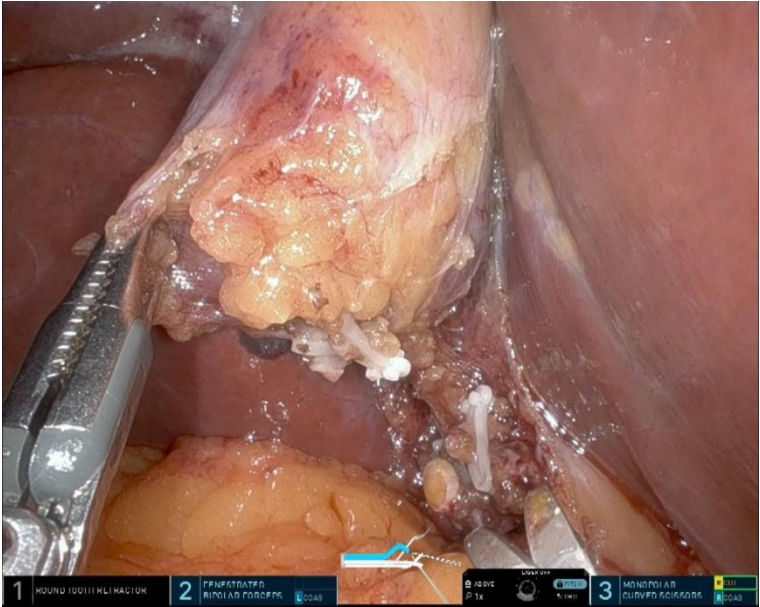
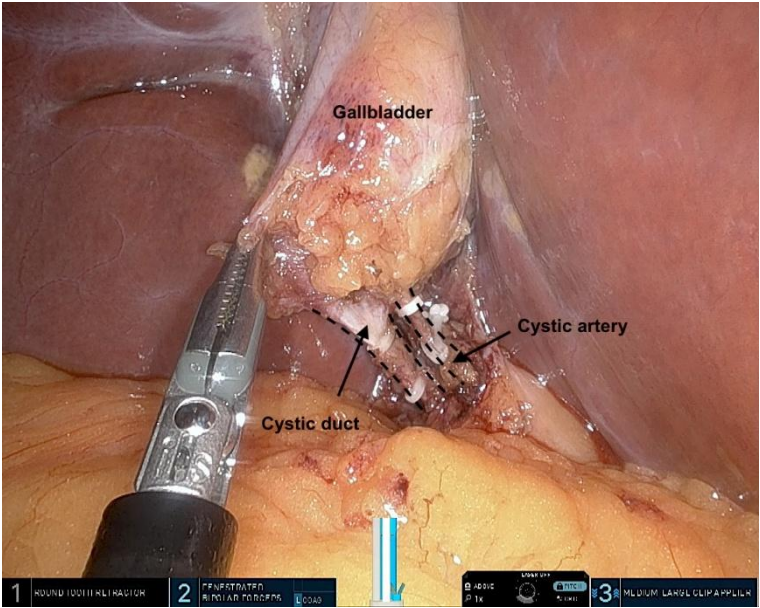
Figure 16. SP trocar positioning during SP Cholecystectomy.



Top: SP trocar in umbilical position – detailed view.

Bottom: SP trocar in umbilical position – panoramic view.

Figure 17. Clipping and transecting the cystic duct and cystic artery.



Top: clipping the cystic duct and artery.
Bottom: transecting the cystic duct and cystic artery.

3 First worldwide series of SP RACE procedures

3.1 Patient characteristics and perioperative data

We analyzed the first 20 consecutive SP RACE procedures performed on adult patients at our institution since April 2024. Demographic data, including age, sex, and body mass index (BMI), were prospectively collected. Tumor location was classified according to the Japanese Classification of Esophageal Cancer (45).

Perioperative data were also prospectively collected and analyzed, including diagnosis, preoperative chemoradiotherapy, tumor-node-metastasis (TNM) stage, resection margin status (R), and Charlson Comorbidity Index (CCI) (46). Additional variables included the total procedure duration, duration of the transcervical mediastinoscopic phase, active instrument time, length of stay in the intensive or intermediate care unit, and readmission to these units. Total procedure duration was defined as the time from abdominal skin incision to completion of the cervical skin suture. The duration of the mediastinoscopic phase was measured from cervical skin incision to cervical skin suture. Active console time represented the cumulative period during which robotic instruments were engaged, reflecting the actual dissection and preparation by the surgeon at the console.

Postoperative pain was assessed using the visual analog scale (VAS), and pain management strategies were recorded. Additionally, total hospital length of stay, perioperative complications, intraoperative mortality, in-hospital mortality, and 30-day and 90-day mortality were recorded. Perioperative complications were classified according to the Esophagectomy Complications Consensus Group (ECCG) (47). All patients underwent laryngoscopy before and after the operation to evaluate for RLNP.

3.2 Statistical analysis

SPSS (Version 30.0.0) was used for all statistical analyses. Continuous variables are presented as mean \pm standard deviation (SD) or median (range), while categorical variables are expressed as percentages.

3.3 Results

3.3.1 Patient characteristics

The demographic characteristics are summarized in Table 1. Ten patients (50%) were female, and the median age was 69 years (range 49–83). The median BMI of the cohort was 22.6 kg/m² (range 15.4–35.3). Six patients (30%) had adenocarcinoma: two located in the middle esophagus and four at the gastroesophageal junction (AEG type I, according to the Siewert classification) (45,48). Fourteen patients (70%) had squamous cell carcinoma: three in the upper esophagus, nine in the middle esophagus, and two in the lower esophagus. Fourteen patients (70%) had undergone neoadjuvant treatment, either chemotherapy according to the FLOT regimen (with or without immunotherapy) or chemoradiotherapy following the CROSS regimen. According to the American Society of Anesthesiologists (ASA) Physical Status Classification System, seven patients (35%) were classified as ASA II, twelve patients (60%) as ASA III, and one patient (5%) as ASA IV. The median Charlson Comorbidity Index (CCI) was 5 (range 3–11), indicating a moderate to high comorbidity burden associated with increased perioperative risk and overall mortality in this cohort.

Table 1. Patient demographics and tumor characteristics.

	N = 20
Age (years) [median (range)]	69 (49 - 83)
Sex [n (%)]	
male	10 (50%)
female	10 (50%)
BMI (kg/m ²) [median (range)]	22.6 (15.4 - 35.3)
American Society of Anesthesiologists (ASA) Physical Status Classification System	
ASA II	7 (35%)
ASA III	12 (60%)
ASA IV	1 (5%)
Charlson comorbidity index (CCI) [median (range)]	5 (3 - 11)
Tumor type and location [n (%)]	
Adenocarcinoma [n (%)]	6 (30%)
Middle esophagus	2 (10%)
AEG type I	4 (20%)
Squamous cell carcinoma [n (%)]	14 (70%)
Upper esophagus	3 (15%)
Middle esophagus	9 (45%)
Lower esophagus	2 (10%)
Neoadjuvant treatment [n (%)]	
No treatment	6 (30%)
Chemotherapy	4 (20%)
Chemoradiotherapy	10 (50%)

3.3.2 Operative parameters

The mean total procedure duration was 332 minutes (± 88), with a mean mediastinoscopic phase duration of 127 minutes (± 100) and an average active console time of 91 minutes (± 48) during this phase (Table 2). On average, three instruments were used during this phase, with an average of two instrument exchanges.

3.3.3 Postoperative complications

No conversions were required during either the abdominal or mediastinoscopic phases of the procedure. No intraoperative complications occurred. Most patients recovered quickly, with a median stay of one day in the intermediate care unit. However, six patients required intensive care unit treatment for more than one day.

In total, sixteen (80%) patients experienced postoperative complications. Five patients (25%) developed pneumonia, and seven (35%) pleural effusion, leading to respiratory insufficiency in four patients (20%). Anastomotic leak occurred in four patients (20%).

RLNP occurred in thirteen patients (65%), was always left-sided, and was classified as Clavien-Dindo grade Ia. Seven patients (35%) experienced complications classified as Clavien-Dindo grade IIIb or higher (Table 2).

3.3.4 Pain management and patient recovery

Pain management was conducted in an interdisciplinary manner with involvement of the anesthesiology team. Only three patients (15%) required patient-controlled analgesia (PCA). The median hospital stay was eight days, and the median intensive care unit (ICU) stay was one day. Four patients (20%) were readmitted to the ICU after transfer to the general ward (Table 2).

3.3.5 Short-term outcomes

Lymph node involvement was confirmed histopathologically in five (25%) patients. Radical (R0) resection was achieved in eighteen patients (90%). The mean number of lymph nodes harvested was 31 (± 7), significantly exceeding current benchmark recommendations (49). In-hospital mortality was 10%, with one patient dying within 30 days of surgery and two others within 90 days (Table 2).

Table 2. Perioperative characteristics and postoperative outcomes of SP RACE.

	N = 20
Total procedure duration (minutes) [mean (SD)]	332 (± 88)
Duration of the mediastinoscopic phase duration (minutes) [mean (SD)]	127 (± 100)
Active console time (minutes) [mean (SD)]	91 (± 48)
Conversion	0 (0%)
Intraoperative complications	0 (0%)
Intensive Care Unit stay (days) [median (range)]	1 (1 – 86)
Pain management	
Peridural analgesia (PDA) [n (%)]	0 (0%)
Paravertebral analgesia [n (%)]	0 (0%)
Patient-controlled analgesia (PCA)	
Postoperative day 1 [n (%)]	2 (10%)
Postoperative day 3 [n (%)]	2 (10%)
Postoperative day 5 [n (%)]	0 (0%)
Complications [n (%)]	16 (80%)
Gastrointestinal	5 (25%)
Anastomotic leak	4 (20%)
Delayed gastric emptying	2 (10%)
Pulmonary	8 (40%)
Pneumonia	5 (25%)
Pleural effusion	7 (35%)
Respiratory insufficiency	4 (20%)
Aspiration	1 (5%)
Cardiac	3 (15%)
Ventricular dysarrhythmia	3 (15%)
Cardiac infarction	1 (5%)
Cardiac arrest	1 (5%)
Thromboembolic	2 (10%)
Pulmonary embolism	2 (10%)
Infection	3 (15%)
Wound infection	3 (15%)
Neurologic/Psychiatric	14 (70%)
laryngeal nerve palsy	13 (65%)
Type Ia	13 (65%)
Delirium tremens	1 (5%)
Clavien-Dindo complication grading system	
< IIIb	9 (45%)
≥ IIIb	7 (35%)
Hospital stays (days) [median (range)]	8 (5 – 86)
Intraoperative mortality [n (%)]	0 (0%)
In-hospital mortality [n (%)]	2 (10%)
30-day mortality [n (%)]	1 (5%)
90-day mortality [n (%)]	1 (5%)
ICU readmission	4 (20%)
Radical (R0) resection [n (%)]	18 (90%)
Number of lymph nodes harvested [mean (SD)]	31 (± 7)

4 Systematic literature review and meta-analysis

This systematic review and meta-analysis adheres to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (50). The analysis was conducted according to a pre-defined protocol, which is available upon request.

4.1 Literature search

MEDLINE, Web of Science and PubMed databases were searched systematically and without any restrictions on date of publication as previously reported (51). Studies comparing the perioperative outcomes of minimally invasive transcervical and transthoracic esophagectomy published until March 2025 were identified. Citations of relevant articles were also screened for additional eligible studies. The used search strategy was: ((single-opening access port) OR (single port) OR (single-port) OR (inflatable) OR (pneumatic) OR (transcervical)) AND (esophagectomy) AND ((carcinoma) OR (cancer)).

4.2 Eligibility criteria

The Population, Intervention, Comparison, Outcome and Study design (PICOS) strategy was used to select studies with the following inclusion criteria:

- Population: adult patients with esophageal cancer undergoing RACE, MICE or MIE for the first time.
- Intervention: RACE, MICE.
- Comparator: MIE.
- Outcome: operation time, complications (RLNP, anastomotic leak, pneumonia, pleural effusion, chyle leak), yield of harvested lymph nodes and hospital stay.
- Study design: any study design (case series, cross-sectional, case-control, and cohort, randomized studies) except study protocols, narrative or systematic reviews, common overviews, letters, case reports, experimental studies, and conference abstracts (52) .

Studies not meeting the inclusion criteria were excluded. Studies analyzing the same patient cohort multiple times without presenting new information were also excluded. Articles were meticulously reviewed to avoid overlapping datasets and duplicate publications. Studies in languages other than English and German were also omitted. Two reviewers screened article titles and abstracts according to the inclusion and exclusion criteria, and the resulting full-text articles were further assessed for eligibility based on the inclusion criteria. Study data were extracted using a standardized data sheet. A third reviewer resolved any discrepancies.

4.3 Quality assessment

The quality of the studies included in the meta-analysis was assessed using the Newcastle-Ottawa Scale (NOS) (53). Selection, comparability and exposure of cases and controls were analyzed using a 9-points score system. Studies scoring between 0 and 1 point were considered of poor quality, between 2 and 6 points of fair quality, and between 7 and 9 of good quality.

4.4 Statistical analysis

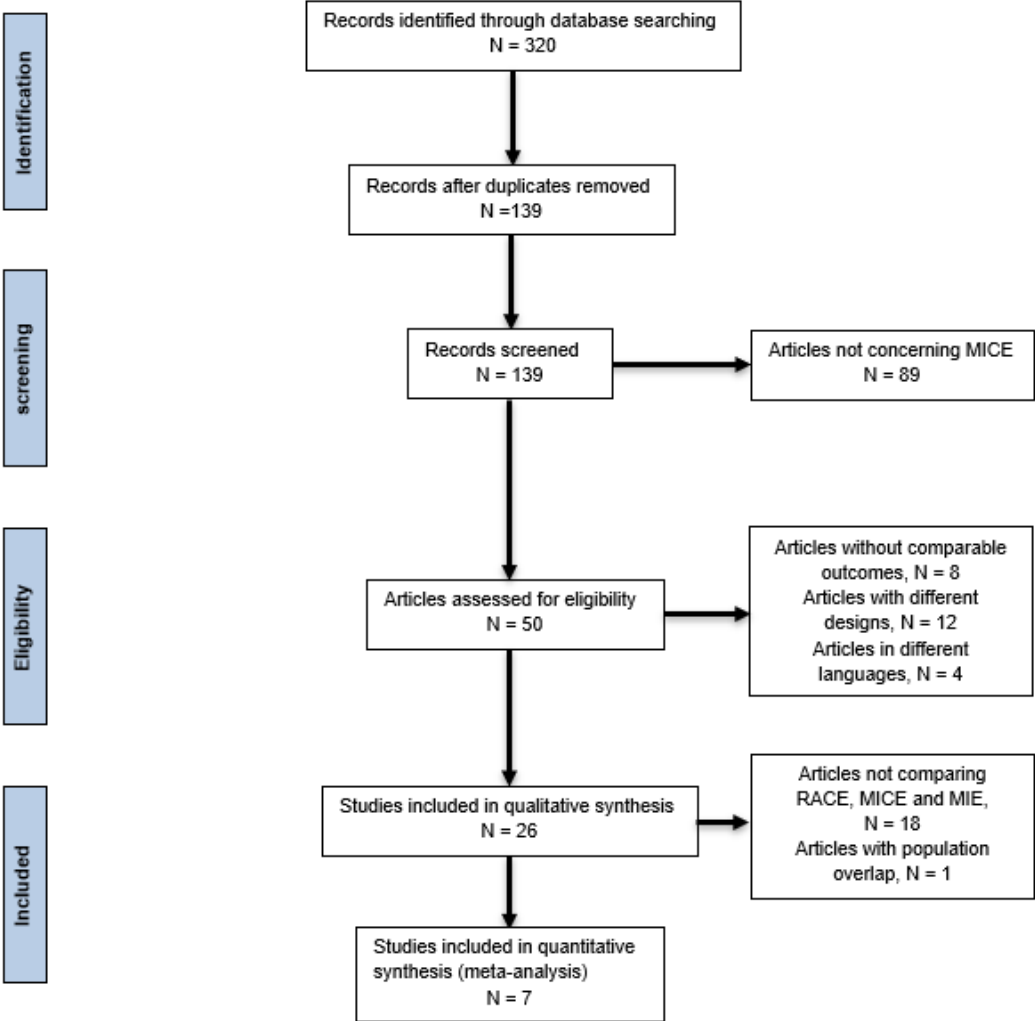
SPSS (Version 30.0.0) was used for all statistical analyses. Potential publication bias was evaluated using funnel plots, with symmetry assessed using Egger's test. Dichotomous data are presented as odd ratios (OR) with 95% confidence intervals (CI). The results of studies were pooled, and an overall estimate of OR was obtained from a random-effects model, as this methodology accounts for differences between studies, even in the absence of statistically significant heterogeneity. In the meta-analysis, the Restricted Maximum-Likelihood estimator was used to analyze continuous variables, with results expressed as standardized mean differences. The random-effect model was used for dichotomous variables, with results expressed as odds ratios (OR). Statistical heterogeneity between included studies was evaluated using the I^2 index. If the I^2 index was between 50% and 75%, heterogeneity was considered moderate, and if the I^2 index was >75%, heterogeneity was considered elevated. A P value <0.05 was considered significant in all analyses.

4.5 Results

4.5.1 Study selection

The literature search identified 320 potentially eligible articles. After removing duplicates and screening titles and abstracts, the full texts of 139 articles were assessed for eligibility. Of these, eighty-nine articles were unrelated to MICE or RACE, eight did not have comparable outcomes, twelve had study designs that did not meet this study's inclusion criteria, and four were in different languages than English or German. This left twenty-six articles that were included in the qualitative analysis. (Figure 18). Eighteen articles did not compare RACE, MICE and MIE, and one article had population overlap with a previous study. Ultimately, seven articles comparing MICE and MIE were included in the meta-analysis.

Figure 18. PRISMA flow chart.



4.5.2 Qualitative analysis.

Table 3 summarizes the characteristics of the articles included in the systematic literature review. Our search identified articles published between 2017 and March 2025. Of these, twenty-two focused on MICE (29–31,38,54–71). Among them, eighteen were retrospective analyses, three had prospective designs, and one was a randomized study. Ten studies analyzed a single cohort and its outcomes (38,54,55,57–61,64,70). Twelve studies compared the outcomes between two or more patient groups (29–31,56,62,63,65–69,71). Eight of these twelve studies compared the results of MICE with MIE (29–31,56,62,65,68,71). Four studies on RACE were identified: two case series and two retrospective studies (36,37,39,40). Three of these analyzed a single cohort and its outcomes, while one compared patients undergoing simultaneous versus sequential approaches. Twenty studies described a unilateral mediastinoscopic approach, while six reported a bilateral approach, with technical variations between centers.

4.5.3 Quality and publication bias assessment

The quality of the cohort studies was assessed using the Newcastle-Ottawa Scale (NOS). All the studies scored between 7 and 9 points and were classified as high quality. They were adequately designed, with follow-up periods sufficient to evaluate the endpoints of the meta-analysis. The objectives and endpoints were clearly defined in all included studies.

Publication bias was found for the lymph node yield outcome (funnel plot, $p = 0.033$, Figure S5, Appendix). No publication bias was found for the other outcomes (funnel plots, $p > 0.05$, Figure S1–S4, S6, Appendix).

4.5.4 Quantitative analysis

The outcomes of the studies included in the systematic literature review regarding MICE and RACE are summarized respectively in Table 4 and Table 5.

A total of 1,141 patients were analyzed.

Table 3. Characteristics of the articles included in the systematic literature review and meta-analysis.

1 st author	Year	Design	OP type	Cohorts	Cervical access	NOS
Fujiwara(54)	2017	retrospective	MICE	-	L: SP med. R: LDV	-
Mori(55)	2017	retrospective	MICE	-	L: SP med. R: LDV	-
Jin(56)	2019	retrospective	MICE	MICE vs MIE	L: SP med. ^a	7/9
Wang(57)	2019	retrospective	MICE	-	L: SP med. R: LDV ^b	-
Nakauchi(37)	2019	case serie	RACE	-	L: SP da Vinci Xi	-
Egberts(36)	2019	case serie	RACE	-	L: SP da Vinci Xi	-
Tokairin(58)	2019	prospective	MICE	-	L: SP med. + LDV R: SP med. + LDV	-
Yin(59)	2020	retrospective	MICE	-	L: SP med. ^a R: 1 Trocar	-
Gan(60)	2021	retrospective	MICE	-	L: SP med.	-
Daiko(38)	2021	retrospective	MICE	-	L: SP med. + LDV R: SP med. + LDV	-
Ye(61)	2021	retrospective	MICE	-	L: SP med.	-
Chen(62)	2022	retrospective	MICE	MICE vs MIE	L: SP med.	9/9
Yin(29)	2022	randomized	MICE	MICE vs MIE	L: SP med. ^a R: 1 Trocar	7/9
Komatsu(63)	2022	retrospective	MICE	CNS vs no CNS	L: SP med. R: DV	7/9
Maeda(64)	2022	retrospective	MICE	-	L: SP med. R: DV	-
Sasaki(65)	2022	retrospective	MICE	MICE vs MIE	L: SP med. + LDV R: SP med. + LDV	9/9
Yuan(66)	2023	retrospective	MICE	Control vs west-china mode group	L: SP med. ^a R: LDV vs 1 Trocar	7/9
Hu(67)	2023	retrospective	MICE	Early vs late experience	L: SP med. R: LDV	7/9
Wang(30)	2023	prospective	MICE	MICE vs MIE	L: SP med. ^a	8/9
Ogawa(68)	2023	retrospective	MICE	MICE vs MIE	L: SP med. R: LDV	9/9
Fujita(39)	2024	retrospective	RACE	-	L: SP da Vinci Xi R: SP da Vinci Xi	-
Tang(69)	2024	retrospective	MICE	Group A vs Group B	L: SP med.	7/9
Daiko(31)	2024	retrospective	MICE	MICE vs MIE	L: SP med. + LDV R: SP med. + LDV	9/9
Fujita(40)	2024	retrospective	RACE	simultaneous vs sequential	L: SP da Vinci Xi R: SP da Vinci Xi	7/9
Vercoulen(70)	2024	prospective	MICE	-	L: SP med.	-
Wang(71)	2024	retrospective	MICE	MICE vs MIE	L: SP med. ^a	9/9

OP, operation; MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive transthoracic esophagectomy; CNS, continuous nerve monitoring; L., left; R., right; SP med., single-port mediastinoscopic; LDV, lymphadenectomy under direct vision. ^a self-made seal protector. ^b routinely not performed

Table 4. Outcomes of the systematic literature review for MICE.

1 st author	N	OP time (min)	Anast. leak	Pneumonia	RLNP	Lymph nodes	R0 resection	Hosp. stay (days)
Fujiwara(54)	60	376.3 ± 75.3	15%	6.7%	33.3% ^{d,e,g}	37 ± 11.8	95%	31 (25-48)
Mori(55)	17	521 (417-612)	29%	0%	0%	10 (2-23)	100%	17 (11-27)
Jin(56)	19	255.52 ± 13.43	10.5%	5.3%	31.6% ^c	-	-	13.00 ± 7.03
Wang(57)	80	191.4 ± 27	8.9%	-	18.8% ^c	21.9 ± 4.1	100%	17.8 ± 8.1
Tokairin(58)	10	615	10%	0%	50% ^{d,e,f,g}	-	-	15.5
Yin(59)	22 ^b	256 ± 31.2	4.5%	-	13.6% ^c	21.6 ± 4.2	-	12.6 ± 2.5
Gan(60)	56	-	8.9%	-	12.5% ^{d,e}	-	-	-
Daiko(38)	16	231 (157-429)	6%	19%	44% ^{d,e,f}	13.5 (5-43)	94%	15 (11-75)
Ye(61)	104	186.7 ± 43.9	8.6%	7.6%	18.2% ^c	22.5 ± 4.5	100%	18.6 ± 8.0
Chen(62)	59	242.0 ± 65.8	13.6%	-	25.4% ^c	18.9 ± 6.0	-	16.0 ± 13.1
Yin(29)	40	200 (175-220)	-	5%	-	-	-	7 (7-8)
Komatsu(63)	41 ^a	418.54 ± 72.68 ^a	-	9.8% ^a	14.6% ^{a,d}	34.15 ± 11.00 ^a	-	23.93 ± 15.00 ^a
Maeda(64)	79 ^b	359.1 ± 57.5	-	5.1%	7.6% ^d	-	-	-
Sasaki(65)	34	550 (354-714)	17.7%	17.7%	38.2% ^c	16.5 (3-44)	-	21.5 (14-122)
Yuan(66)	80 ^a	290.31 ± 45.39 ^a	5% ^a	18.75% ^a	10% ^{a,c}	30.45 ± 9.90 ^a	100% ^a	15.04 ± 23.64 ^a
Hu(67)	108	310 (216-525)	12%	-	11.1% ^c	23.9 ± 8.4	100%	16 (7-68)
Wang(30)	30	217.2 ± 38.6	6.7%	3.3%	3.3% ^c	14.5 ± 5.3	-	9.0 (9-11)
Ogawa(68)	60	403 (348-475)	11.7%	1.7%	16.7% ^c	40 ± 9.4	98.3%	17 (13-23)
Tang(69)	38 ^a	205.13 ± 18.57 ^a	10.5% ^a	0% ^a	15.8% ^a	19.45 ± 3.27 ^a	86.8% ^a	19.86 ± 7.73 ^a
Daiko(31)	27 ^b	254 ± 104	7.4%	25%	29.6% ^{d,e,f}	19.1 ± 7.7	100%	16 (14-21)
Vercoulen(70)	75	360 (311-390)	7%	5%	44% ^d	29 (22-37)	96%	8.5 (7-11)
Wang(71)	36 ^b	221.72 ± 47.09	-	-	-	-	-	17.28 ± 7.77

^a Result calculated combining two groups of patients. ^b Possibly the population partially overlap with the one of previous studies.

^c Symptomatic RLNP. ^d RNLN confirmed through laryngoscopy. ^e left RNLN. ^f right RNLN. ^g bilateral RNLN.

^h Arithmetic mean. N, number of patients; OP time, Operation time; RLNP, recurrent laryngeal nerve palsy.

Table 5. Outcomes of the systematic literature review for RACE.

1 st author	N	OP time (min)	Anast. leak	Pneumonia	RLNP	Lymph nodes	R0 resection	Hosp. stay (days)
Nakauchi(37)	6	805 (593-1145)	16.6%	16.6%	33.3% ^c	20.5 (10-36)	100%	17.5 (15-26)
Egberts(36)	4	344 (292-433)	25%	25%	25% ^c	24.5 ± 7.72	100%	18 (11-28)
Fujita(39)	10	472.7 ± 28.4	20%	0%	10% ^d	-	-	22 (12-43)
Fujita(40)	30 ^a	-	13.3% ^a	6.6% ^a	13.3% ^{a,d}	-	-	19 ± 15 ^a

^a Result calculated combining two groups of patients. ^b Possibly the population partially overlap with the one of previous studies.

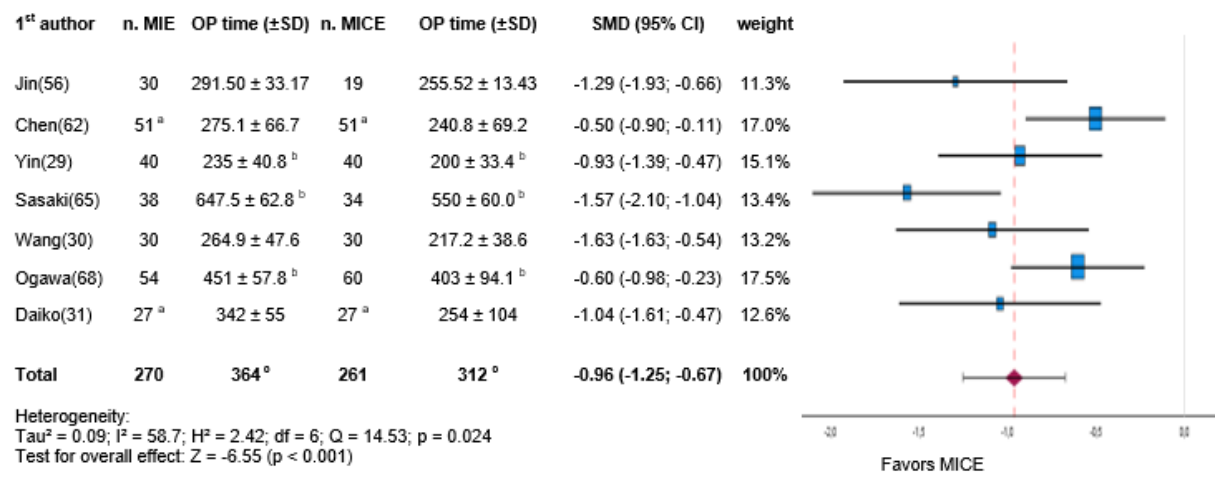
^c Symptomatic RLNP. ^d RNLN confirmed through laryngoscopy. ^e left RNLN. ^f right RNLN. ^g bilateral RNLN.

^h Arithmetic mean. N, number of patients; OP time, Operation time; RLNP, recurrent laryngeal nerve palsy.

4.5.5 Operation time

In the meta-analysis of operation time (Figure 19), seven studies were analyzed, comprising 261 patients in the MICE group and 270 in the MIE group (29–31,56,62,65,68). All studies reported significantly shorter operation times for MICE compared to MIE, with a mean standardized difference of -0.96 ($p < 0.001$). The average operation times for the MICE and MIE groups were 312 and 364 minutes, respectively. Study heterogeneity was moderate and statistically significant ($I^2 = 58.7\%$, $p = 0.024$).

Figure 19. Meta-analysis of operation time.

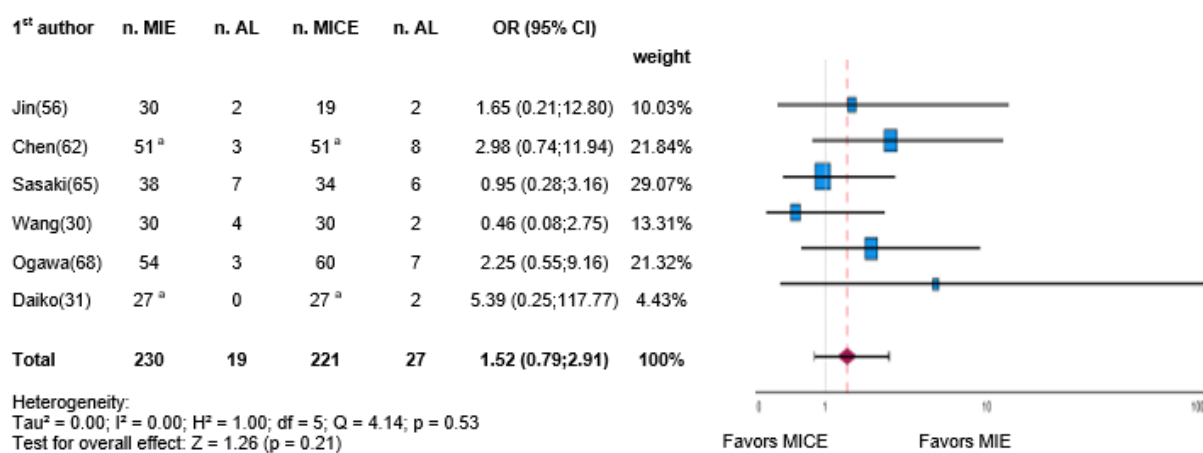


^a Propensity score-matched analysis Groups. ^b The standard deviation was estimated due to a lack of data. ^c weighted mean.
 MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive transthoracic esophagectomy; OP, Operation;
 SD, Standard Deviation; SMD, Standardized Mean Difference; CI, Confidence Interval

4.5.6 Anastomotic leak rate

For the meta-analysis of anastomotic leak rates (Figure 20), six studies were included, comprising 221 patients in the MICE group and 230 in the MIE group (30,31,56,62,65,68). Two studies reported lower leak rates for MICE compared to MIE (30,65), while four reported higher rates (31,56,62,68). The average anastomotic leak rates were 12.2% for MICE and 8.3% for MIE. Neither the test for overall effect nor the heterogeneity between studies reached statistical significance.

Figure 20. Meta-analysis of anastomotic leak rate.

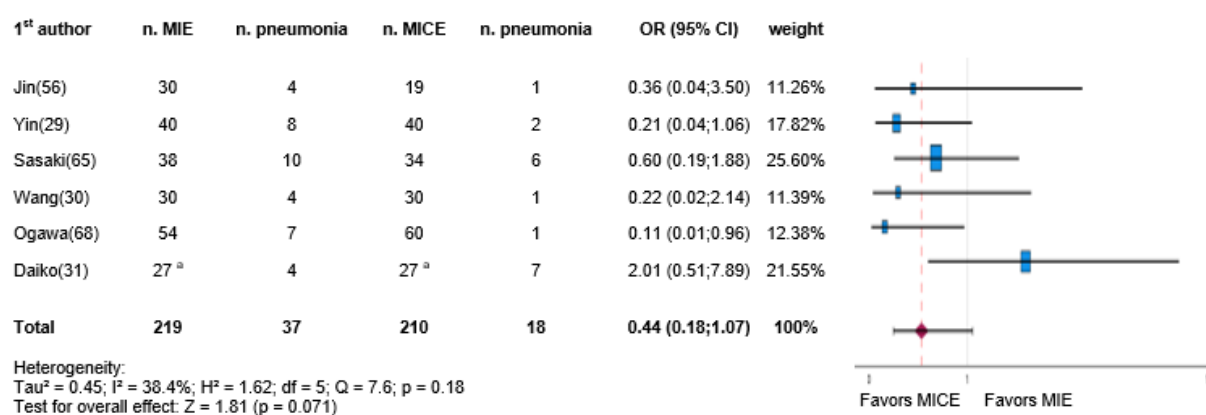


^a Propensity score-matched analysis Groups. MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive transthoracic esophagectomy; AL, Anastomotic Leak; CI, Confidence Interval.

4.5.7 Pneumonia rate

Regarding the meta-analysis of pneumonia rate (Figure 21), six studies were included, with 210 in the MICE and 219 patients in the MIE group (29–31,56,65,68). Five studies reported lower pneumonia rates for MICE compared to MIE (29,30,56,65,68), while one reported a higher rate (31). The average pneumonia rates for the MICE and MIE groups were 8.3% for MICE and 16.9% MIE. Although the tests for overall effect and heterogeneity were not statistically significant, there was a trend toward lower pneumonia rates in the MICE group ($p = 0.071$).

Figure 21. Meta-analysis of pneumonia rate.



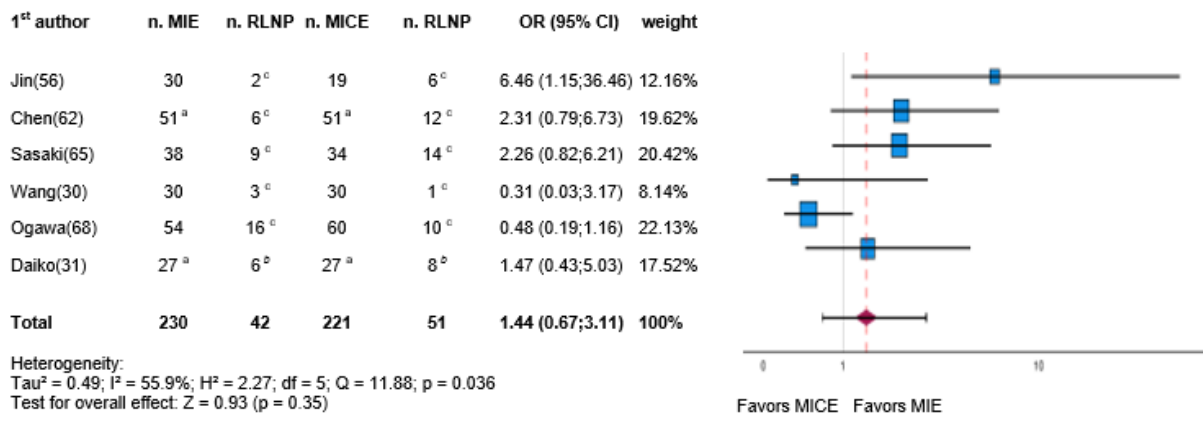
^a Propensity score-matched analysis Groups. MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive transthoracic esophagectomy; CI, Confidence Interval.

4.5.8 Recurrent laryngeal nerve palsy rate

RLNP was described as postoperative hoarseness in twelve studies (30,36,37,56,57,59,61,62,65–68), confirmed via laryngoscopy in ten (31,38–40,54,58,60,63,64,70), and not specified in four (29,55,69,71). Among the studies with laryngoscopic confirmation, five reported left-sided palsy (31,38,54,58,60), three right-sided (31,38,58), two bilateral (54,58), and five did not report the affected side (39,40,63,64,70).

Regarding the meta-analysis of RLNP rate (Figure 22), six studies were included, with a 221 in the MICE and 230 patients in the MIE group (30,31,56,62,65,68). Two studies reported lower RLNP rates for MICE compared to MIE (30,68), while four reported higher rates (31,56,62,65). The average RLNP rates were 23.1% for MICE and 18.3% for MIE. The test for overall effect was not significant, and a significant heterogeneity among studies was found ($I^2 = 55.9\%$, $p = 0.036$).

Figure 22. Meta-analysis of recurrent laryngeal nerve palsy rate.

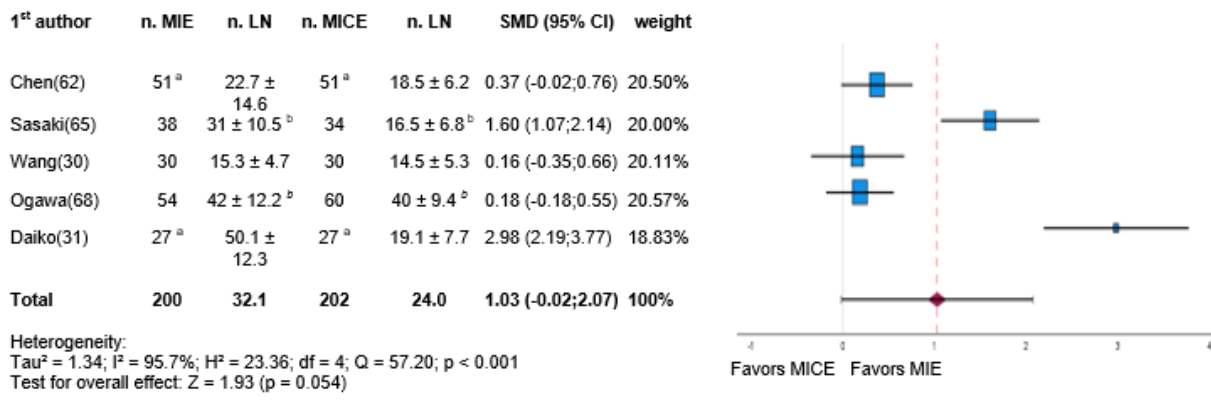


^a Propensity score-matched analysis Groups. ^b RLNP confirmed through laryngoscopy. ^c Symptomatic RLNP. MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive Transthoracic esophagectomy; CI, Confidence Interval; RLNP, Recurrent Laryngeal Nerve Palsy.

4.5.9 Lymph node yield

Regarding the meta-analysis of lymph node yield (Figure 23), five studies were included, with 202 patients in the MICE group and 200 in the MIE group (30,31,62,65,68). All studies reported a lower lymph node yield for MICE compared to MIE, with a mean standardized difference of 1.03. The test for overall effect was not statistically significant ($p = 0.054$). The average lymph node yields for the MICE and MIE groups were 24.0 and 32.1, respectively. The heterogeneity among the studies was high ($I^2 = 95.7\%$, $p < 0.001$). Evidence of publication bias was found (funnel plot, $P = 0.033$, Figure S5, Appendix).

Figure 23. Meta-analysis of lymph node yield.



^a Propensity score-matched analysis Groups. ^b The standard deviation was estimated due to a lack of data. MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive Transthoracic esophagectomy; CI, Confidence Interval; LN, Lymph Nodes; SD, Standard Deviation; SMD, Standardized Mean Difference.

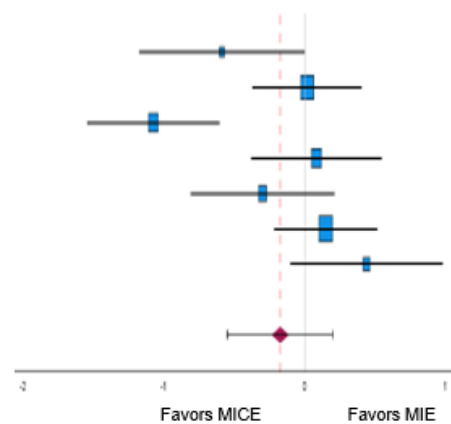
4.5.10 Hospital Stay

For the meta-analysis of hospital stay (Figure 24), data from seven studies were included, comprising 261 patients in the MICE group and 270 in the MIE group (29–31,56,62,65,68). Three studies reported a shorter hospital stay for MICE (29,30,56), while four reported a longer stay (31,62,65,68). The mean standardized difference was -0.17, and the overall effect was not statistically significant ($p = 0.361$). The average hospital stay was 14.7 in both MICE and MIE groups. Study heterogeneity was high ($I^2 = 78\%$, $p < 0.001$).

Figure 24. Meta-analysis of hospital stays.

1 st author	n. MIE	Hosp. stay	n. MICE	Hosp. stay	SMD (95% CI)	weight
Jin(56)	30	16.90 ± 6.19	19	13.00 ± 7.03	-0.59 (-1.18;0.00)	12.75%
Chen(62)	51 ^a	16.7 ± 10.5	51 ^a	16.9 ± 13.8	0.02 (-0.37;0.40)	15.48%
Yin(29)	40	8 ± 1.1 ^b	40	7 ± 0.7 ^b	-1.07 (-1.54;-0.60)	14.36%
Sasaki(65)	38	20 ± 18.2 ^b	34	21.5 ± 18.0	0.08 (-0.38;0.54)	14.46%
Wang(30)	30	10 ± 4.4 ^b	30	9 ± 1.5 ^b	-0.30 (-0.81;0.21)	13.82%
Ogawa(68)	54	16 ± 5.9 ^b	60	17 ± 7.4 ^b	0.15 (-0.22;0.52)	15.74%
Daiko(31)	27 ^a	14 ± 3.7 ^b	27 ^a	16 ± 5.2 ^b	0.44 (-0.10;0.98)	13.39%
Total	270	14.7	261	14,7	-0.17 (-0.55;0.20)	100%

Heterogeneity:
 Tau² = 0.20; I² = 78%; H² = 4.54; df = 5; Q = 26; p < 0.001
 Test for overall effect: Z = -0.91 (p = 0.361)



^a Propensity score-matched analysis Groups. ^b The standard deviation was estimated due to a lack of data. MICE, Minimally invasive transcervical esophagectomy; MIE, Minimally invasive transthoracic esophagectomy; CI, Confidence Interval; LN, Lymph Nodes; SD, Standard Deviation; SMD, Standardized Mean Difference.

5 Discussion

This study reports on the successful implementation of the da Vinci SP system into clinical practice at the Department of General, Visceral and Transplant Surgery at the University Hospital of Mainz. Notably, the world's first series of SP RACE procedures utilizing the da Vinci SP system was safely performed. In our analysis of the first consecutive twenty SP RACE procedures, no conversions to open or transthoracic procedures were observed, and no intraoperative complications or deaths occurred, demonstrating the feasibility and safety of this new surgical technique for the treatment of esophageal cancer. The rate of Clavien-Dindo \geq IIIb complications was comparable to the complication rates of the McKeown procedure during the learning curve phase (72,73). Pneumonia and anastomotic leakage are the leading complications after esophageal surgery; in this study, their rates were consistent with those reported in literature (72,73). However, the incidence of RLNP is a quality benchmark (25). Although the RLNP rate was high in this study, all cases were classified as type Ia left-sided. RLNP based on postoperative laryngoscopy and required only logopedic treatment.

Another highlight of this study is pain management. No patient required epidural or intercostal catheters for analgesia. Only two patients required Patient-controlled analgesia (PCA) on postoperative day three, while all others were treated with oral or intravenous analgesics on demand. This resulted with very fast mobilization of the patients, early transfer to the normal ward, and discharge for patients without complications – the earliest being on postoperative day five. The high ICU readmission rate was due to complications, such as respiratory insufficiency following pulmonary infection, anastomotic leak, and pulmonary embolism. Most of the patients recovered and were successfully discharged after treatment of the complications. However, one patient died four days after the procedure due to a fulminant pulmonary embolism, and another died in the ICU 86 days postoperatively from multiorgan failure caused by sepsis resulting from pneumonia and anastomotic insufficiency. Both patients had high CCI (5 and 11, respectively) reflecting their multimorbidity.

The average lymph node yield in this series surpassed the benchmark recommendations (49). Comparing these results with those calculated in the systematic literature review and meta-analysis, it could be argued that SP RACE enables more radical lymphadenectomy due to reduced collisions between robotic arms in narrow spaces and the magnified view of the operation field. The rate of radical R0 resections may have been influenced by the learning curve effect observed in this study, as well as in other studies presenting pioneering surgical approaches (38,54,69). However, the analysis of the learning curve was beyond the scope of this study.

Several studies in the literature have reported on the operative times for esophagectomies. Biere et al. measured an average duration of 299 minutes for open esophagectomy compared

to 329 minutes for minimally invasive esophagectomy (18). Van der Sluis et al. investigated the learning curve of three-stage RAMIE in a cohort of 312 cases and, after the completion of the learning curve, found an average operative times of 375 minutes (72). Our meta-analysis showed significantly shorter operation times for MICE compared to MIE (312 and 364 minutes, respectively). In our cohort we observed a total procedure duration of 332 minutes, which is shorter compared to published data on RACE, especially when sequential procedures are considered (36,37,39,40). Improved results could potentially be achieved by overlapping the laparoscopic and transcervical mediastinoscopic phases to allow simultaneous procedures – a strategy demonstrated by Grimminger et al. and further analyzed in the study by Fujita et al. (34,40). In their study, this approach significantly reduced total procedural time to approximately 150 minutes. The effect of the learning curve, especially for complex and novel surgical techniques, must not be underestimated. The impact of the learning curve on total procedure duration in MICE has been analyzed by Hu et al. who reported significant differences between early and late experience groups (67). In the early experience group, the abdominal and transcervical mediastinoscopic phases lasted 118 and 146 minutes, respectively, while in the late experience group, these durations were reduced to 99 and 124, respectively.

This study has several limitations. In addition to its retrospective design, a direct comparison between RACE, MICE and MIE was not feasible due to lack of published studies on RACE. Furthermore, the systematic review and meta-analysis were limited by the cohort sizes of the included studies. The decision not to directly compare the SP RACE patient cohort with patients undergoing multi-port robot-assisted esophagectomy – a procedure that has been well established at our centers after only 22 cases (74) – was primarily due to the limited number of SP RACE procedures performed to date. Peri- and postoperative data, particularly complication rates, may have been influenced by the steep learning curve associated with the SP RACE technique. Additionally, the recent adoption of the da Vinci SP RACE platform and the relatively short follow-up period prevented us from evaluating its impact on overall survival and disease recurrence. Therefore, future studies are necessary to validate the findings of this study, to standardize operative protocols, to refine surgical techniques, and to define appropriate indications for SP RACE. Nonetheless, this study demonstrates that SP RACE can be successfully integrated into high-volume centers, expanding surgical options for patients with proximal esophageal tumors and significant comorbidities. The da Vinci SP robotic system offers innovative treatment options also for patient with distal and junctional esophageal cancer through the novel technique named SP SC RAMIE. It represents a viable alternative to the multi-port transthoracic Ivor Lewis esophagectomy, offering a safe approach for patients with tumors of the distal esophagus and enabling the benefits of enhanced recovery pathways (42,75).

6 Summary

This study reports on the successful implementation of the da Vinci SP system into clinical practice at the Department of General, Visceral and Transplant Surgery at the University Hospital of Mainz. Notably, the world's first series of SP RACE procedures was safely performed. This technique has the potential to expand surgical options for patients previously deemed unsuitable for surgery – particularly those with pulmonary comorbidities – by eliminating the need for one-lung ventilation. Moreover, it offers notable advantages, including short operating times, fast postoperative recovery, and excellent lymph node yield. Importantly, postoperative pain was minimal despite the absence of epidural or paravertebral analgesia, underscoring the effectiveness of the SP RACE technique in minimizing pain through its minimally invasive approach.

In comparing MICE and MIE via literature review and meta-analysis, a significantly shorter operation duration for MICE compared to MIE was observed. When comparing our results with the available published data on RACE and RAMIE – taking the learning curve into account – we noticed shorter operative time in our first series.

While the first results are promising, further studies are needed to validate these findings, fully explore the potential of the SP RACE technique, and assess long-term outcomes. The results of this study highlight the ongoing progress in the surgical treatment of esophageal cancer. In addition, continued innovations in SP system technology – such as the integration of vessel-sealing energy devices, robotic staplers, and artificial intelligence for intraoperative guidance and workflow optimization – may help further reduce the duration of the complex transcervical mediastinoscopic procedure.

7 Zusammenfassung

Diese Studie berichtet über die erfolgreiche Implementierung des da Vinci SP-Systems in die klinische Praxis an der Klinik für Allgemein-, Viszeral- und Transplantationschirurgie des Universitätsklinikums Mainz. Bemerkenswerterweise wurde die weltweit erste Serie von SP RACE-Eingriffen sicher durchgeführt. Diese Technik hat das Potenzial, das chirurgische Behandlungsspektrum für Patienten zu erweitern, die zuvor aufgrund pulmonaler Komorbiditäten als inoperabel galten – insbesondere durch den Verzicht auf eine Einlungenventilation. Darüber hinaus bietet sie bedeutende Vorteile wie kurze Operationszeiten, eine schnelle postoperative Erholung sowie eine exzellente Lymphknotenausbeute. Hervorzuheben ist zudem, dass die postoperativen Schmerzen trotz fehlender epiduraler oder paravertebraler Analgesie minimal waren, was die Effektivität der SP RACE-Technik im Hinblick auf eine schmerzarme, minimalinvasive Herangehensweise unterstreicht.

Im Vergleich von MICE und MIE anhand einer Literaturübersicht und Metaanalyse zeigte sich eine signifikant kürzere Operationsdauer für MICE im Vergleich zu MIE. Vergleicht man unsere Ergebnisse mit den bisher veröffentlichten Daten zu RACE und RAMIE – unter Berücksichtigung der Lernkurve – so zeigen sich in unserer ersten Serie bereits kürzere Operationszeiten.

Auch wenn die ersten Ergebnisse vielversprechend sind, sind weitere Studien notwendig, um diese Erkenntnisse zu validieren, das volle Potenzial der SP RACE-Technik zu erforschen und Langzeitergebnisse zu bewerten. Die Ergebnisse dieser Arbeit verdeutlichen den fortschreitenden Wandel in der chirurgischen Behandlung des Ösophaguskarzinoms. Darüber hinaus könnten fortlaufende technologische Innovationen des SP-Systems – wie die Integration von Gefäßversiegelungstechnologien, robotischen Klammernahtgeräten und künstlicher Intelligenz zur intraoperativen Navigation und Optimierung von Arbeitsabläufen – dazu beitragen, die Dauer dieses komplexen mediastinoskopischen Eingriffs weiter zu verkürzen.

8 List of abbreviations

MIE - Minimally Invasive Esophagectomy

RAMIE - Robotic-Assisted Minimally Invasive Esophagectomy

RCT - Randomized controlled trial

SCC - Squamous cell carcinoma

ADC - Adenocarcinoma

SP – Single-Port

RACE - Robotic-Assisted Cervical Esophagectomy

SC RAMIE - Subcostal Robotic-Assisted Minimally Invasive Esophagectomy

ICG - Indocyanine green

EEA Stapler - End-to-end anastomosis stapler

Endo-GIA Stapler - Endoscopic gastrointestinal anastomosis stapler

MICE - Minimally Invasive Transcervical Esophagectomy.

RLN - Recurrent laryngeal nerve

RLNP - Recurrent laryngeal nerve palsy

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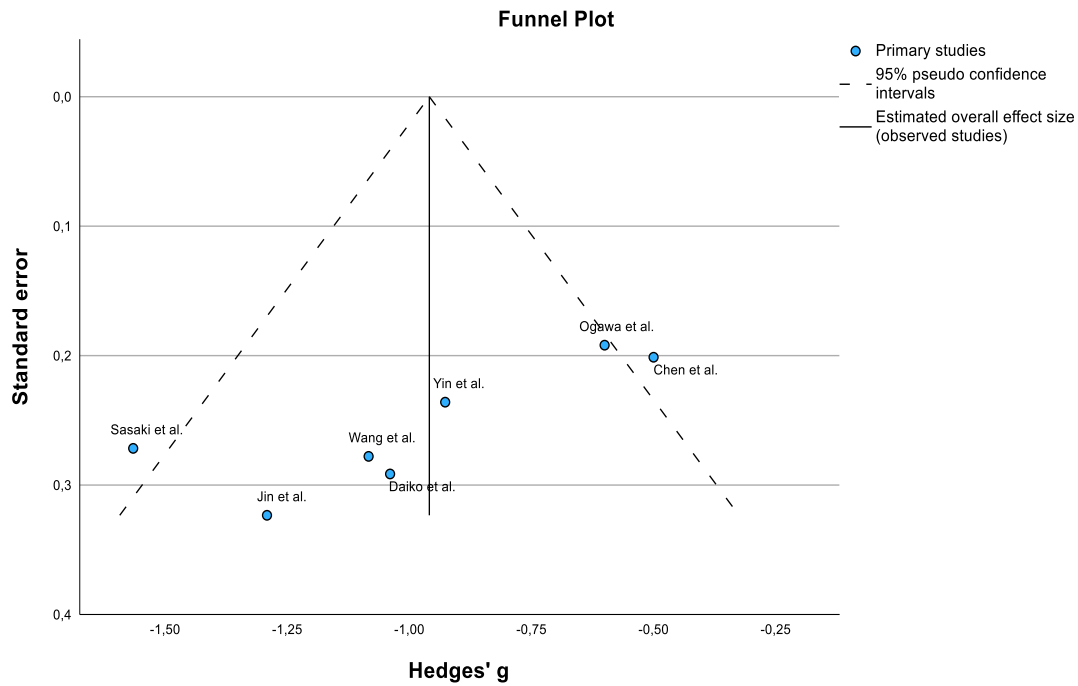
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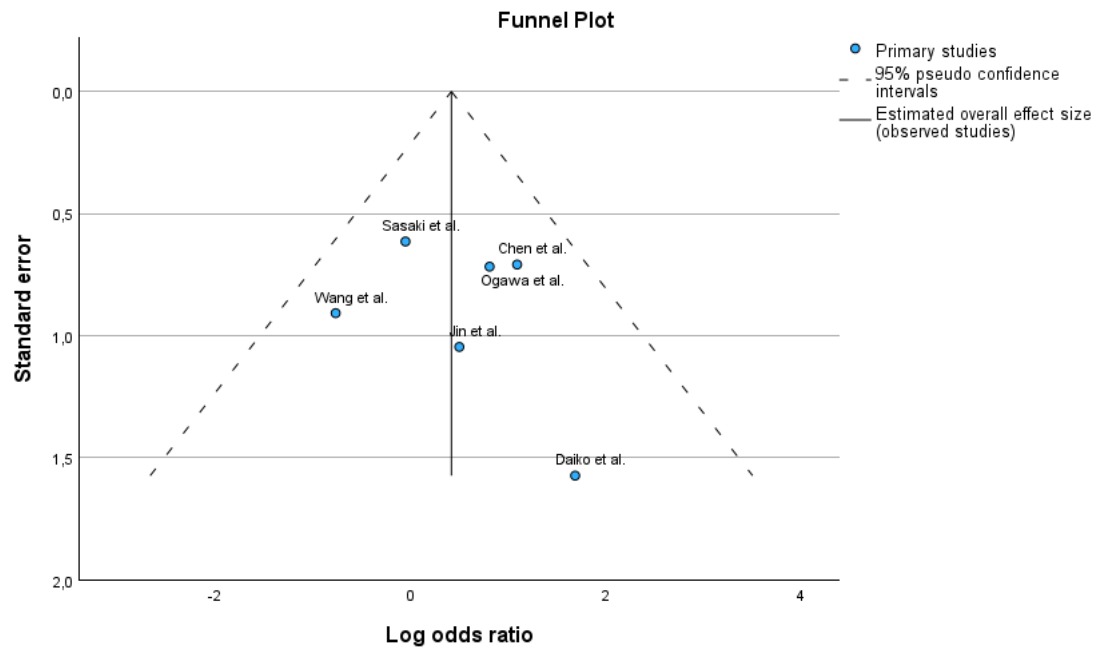
10 Appendix

Figure S1. Funnel plot of operation time.



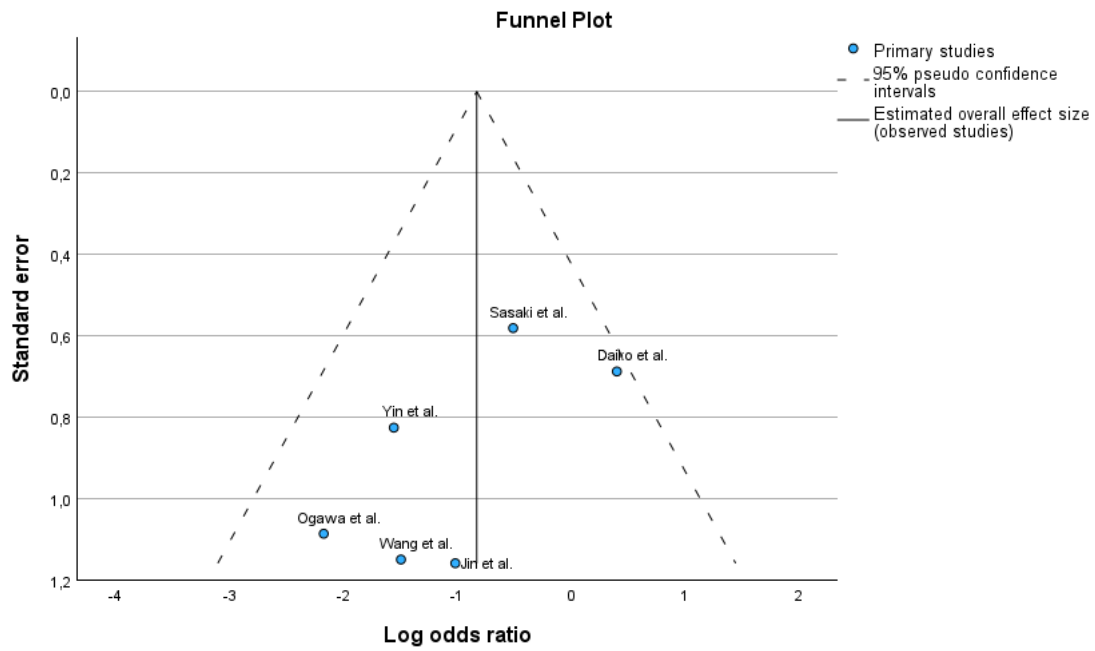
Egger's regression-based test: $p = 0.572$

Figure S2. Funnel plot of anastomotic leak rate.



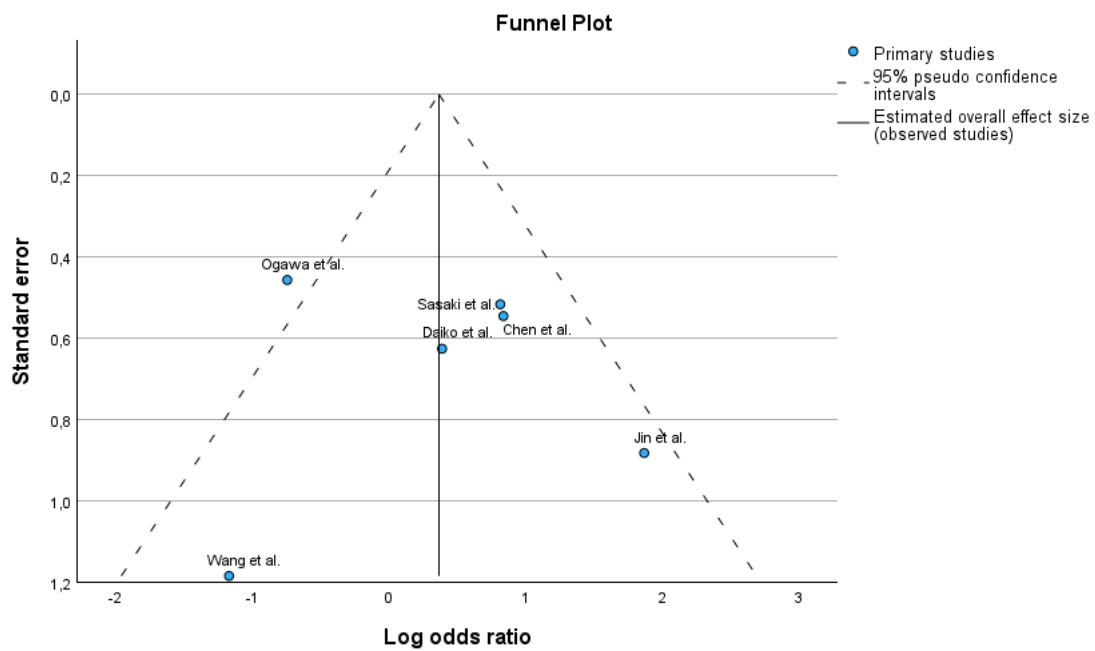
Egger's regression-based test: $p = 0.665$

Figure S3. Funnel plot of pneumonia rate.



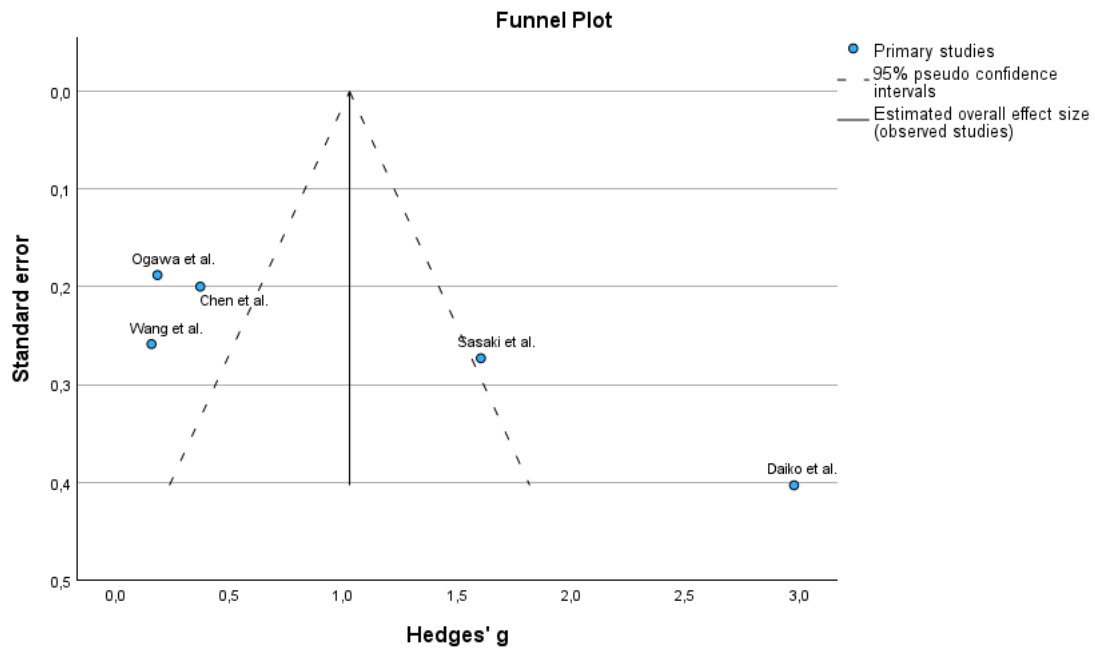
Egger's regression-based test: $p = 0.186$

Figure S4. Funnel plot of recurrent laryngeal nerve palsy rate.



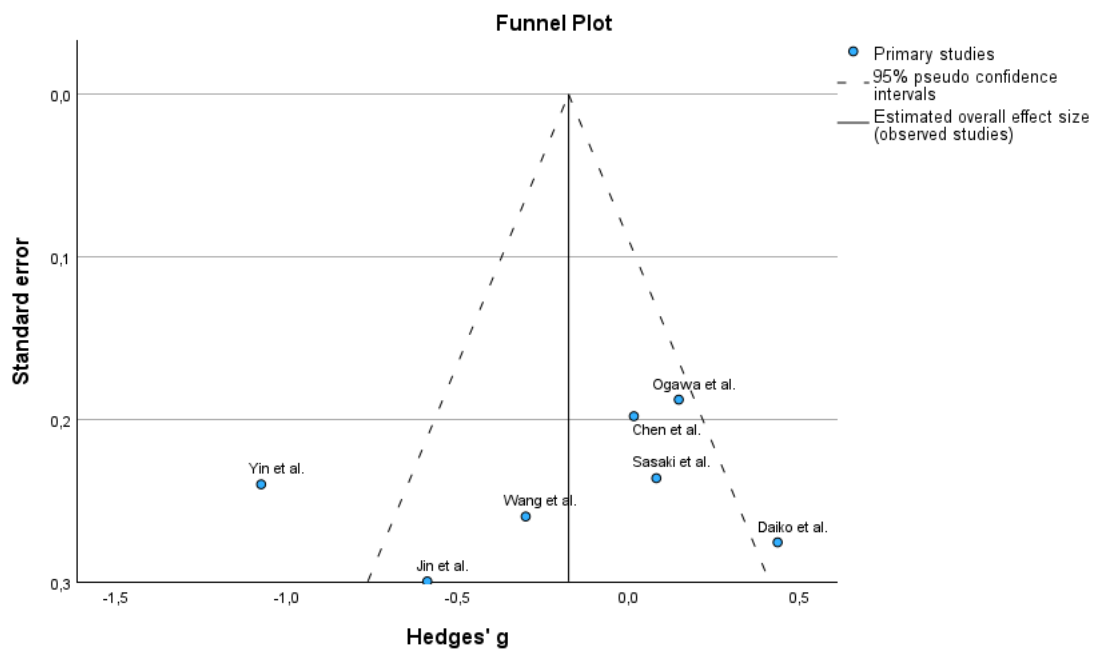
Egger's regression-based test: $p = 0.962$

Figure S5. Funnel plot of lymph node yield.



Egger's regression-based test: $p = 0.033$

Figure S6. Funnel plot of hospital stays.



Egger's regression-based test: $p = 0.569$

11 Acknowledgments

I would first like to thank Herr Prof. Grimminger for his unwavering support and trust in my abilities. He not only introduced me to the exciting world of robotic esophagectomies, but also supported me in securing a position as a surgical resident and advancing my scientific career through continuous opportunities for research and participation in congresses. I would also like to express my gratitude to Herr Prof. Lang, who gave me the opportunity to work at his center and to meet many colleagues who have contributed to my professional growth. Special thanks go to Dr. med. Hadzijusufovic, who is always willing to explain the intricacies of what is happening in the operating room, and to PD Dr. med. Lozanovski, who helps me develop high-quality scientific work every day. I am also grateful to Dr. med. Renger, who supported the revision of this and other scientific works. Finally, I thank all other members of the Upper GI team and the Department of General, Visceral and Transplant Surgery at the University Medical Center of Johannes Gutenberg University Mainz, for their constant support in my journey to learn and grow in the field of surgery.



12 Curriculum Vitae

Arbeitserfahren

- November 2024 – heute **Assistenzarzt in der Allgemein-, Viszeral- und Transplantationschirurgie**
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Uniklinik Mainz
Schwerpunkt: Literaturrecherche, Datenerfassung und Analyse, Teilnahme an Operationen und Stationsaktivitäten
- April 2023 – August 2023 **Stationsarzt im Bereitschaftsdienst**
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Red-Cap

gut

SPSS

gut

GraphPad Prism

gut

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Single-Port daVinci Robot-Assisted Cervical Esophagectomy (SP-RACE) - How to Do

It. Hadzijusufovic, E., Lozanovski, V. J., Griemert, E. V., **Bellaio, L.**, Lang, H., & Grimminger, P. P. (2024).

The Thoracic and cardiovascular surgeon

Single-Port Subcostal Robot-Assisted Minimally Invasive Esophagectomy-How to Do It?

Hadzijusufovic, E., Lozanovski, V. J., **Bellaio, L.**, Tagkalos, E., Uzun, E., Griemert, E. V., Lang, H., & Grimminger, P. P. (2025).

The Thoracic and cardiovascular surgeon

Vorträge

Single-Port Subcostal Robotic Assisted Minimally Invasive Esophagectomy – SP SC RAMIE.

Präsentiert auf dem Kongress „ISDE 20th Word Congress for Esophageal Disease“.

Edinburgh, Schottland, 22.-24. September 2024.

Single-Port Subcostal Robotic Assisted Minimally Invasive Esophagectomy – SP SC RAMIE

Präsentiert auf dem Kongress “ESDE Conference 2025”

Amsterdam, Niederlande, 11.-13. Mai 2025

Robotic Single-Port Toupet fundoplication: minimally invasive approach for GERD treatment

Präsentiert auf dem Kongress “ESDE Conference 2025”

Amsterdam, Niederlande, 11.-13. Mai 2025

SP RACE - First series, literature review and meta-analysis

Präsentiert auf dem Kongress “ESDE Conference 2025”

Amsterdam, Niederlande, 11.-13. Mai 2025

Seminare

Implementation of the SP DaVinci system in the university hospital of Mainz.

Universitäre Vorlesung.

Mainz, 20. November 2024 (8:30-13:00).

Videos

Robotic Single-Port Toupet fundoplication: implementation of the da Vinci SP system in the treatment of gastroesophageal reflux disease (GERD)

L Bellaio, E Hadzijasufovic, VJ Lozanovski, DG Alves, F Renger, PP Grimminger

Epublication WebSurg.com, Nov 2025;25(11).

URL: <https://websurg.com/en/doi/vd01en7613?token=67beeaf1c15c4>

Mainz, den 26.07.2025

Luca Bellaio