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RESEARCH

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Robot-assisted functional minimally invasive radical resection of esophageal cancer

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Abstract

Background Recently, robot-assisted surgical systems have become more and more popular, but have not been reported in functional minimally invasive radical resection of esophageal cancer,which preserves the mediastinal pleura, the azygos arch, bronchial artery, and pulmonary branch of the vagus nerve.

Methods Retrospective analysis of all patients in our hospital who underwent surgery for esophageal cancer from September 2022 to February 2024. Robot-assisted functional minimally invasive esophagectomy (RAFMIE)was performed for 44 patients who were compared with 66 functional minimally invasive esophagectomy (FMIE) cases.

Result Significantly, shorter operation time was taken in RAFMIE (222.98 ± 28.02 vs 250.45 ± 30.25 min $P < 0.001$), thoracic operation time (75.50 ± 14.23 vs 89.59 ± 16.34 min $P < 0.001$), abdominal operation time (51.93 ± 14.18 vs 71.75 ± 14.85 min $P < 0.001$). Both groups were equal regarding intraoperative blood loss (82.73 ± 57.23 vs 94.55 ± 60.19 ml, $P = 0.286$), radical resection (R0) rate (97.73% vs 96.97%, $P = 0.813$) and total lymph node yield (25.45 ± 7.40 vs 21.03 ± 7.00, $P = 0.013$). Postoperative hospital stay (9.75 ± 2.23 vs 10.47 ± 2.72, $P = 0.402$); incidence of postoperative complications (25.76% vs 20.45%, $P = 0.519$).

Conclusion Early results suggest that RAFMIE is safe and feasible for the treatment of esophageal cancer. The operation time of RAFMIE is shorter than FMIE, and the lymph node dissection results are better. Long-term results need to be further investigated.

Keywords Robot-assisted surgical systems, Robot-assisted functional minimally invasive esophagectomy (RAFMIE), Esophageal malignancy, Thoracic operative time

Introduction

Esophageal malignancies are the most aggressive among all gastrointestinal malignancies. The 5-year overall survival rates range from 15 to 25%. Oncological esophagectomy is a crucial element of curative treatment for resectable esophageal cancer [1–3]. Retrospective and meta-analysis studies have shown clear advantages of minimally invasive esophagectomy (MIE) in terms of improved clinical outcomes, such as shorter hospital stays, lower incidence of respiratory complications, and lower overall incidence, among others [4]. Our team previously proposed the concept of functional minimally invasive esophagectomy(FMIE), a refined surgical technique that involves preserving the mediastinal pleura, azygos arch, vagus nerve, pulmonary branches, and bronchial arteries, and confirmed its feasibility [5].

In recent years, the use of robot-assisted surgery systems (RASS) has increased in minimally invasive surgeries, including minimally invasive radical esophagectomy [6]. RASS provides high-definition vision, multi-angle flexibility, and high stability, which can facilitate better

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resection of tumors and metastatic lymph nodes in the narrow mediastinal space and potentially improve long-term prognosis. FMIE requires delicate operation and a higher surgical field of view for the repair of the mediastinal pleura while preserving vital structures, and is well-suited to the capabilities of RASS.

To determine the feasibility and superiority of robot-assisted surgical systems over traditional endoscopic techniques in FMIE, we conducted a retrospective analysis of data from two groups of surgical patients. Our study confirmed that RASS can significantly shorten the operation time and has more advantages in lymph node dissection.

Methods

Patients

We collected perioperative data of 110 patients with esophageal cancer who underwent FMIE in our department from September 2022 to February 2024. Among them, 44 patients completed robot-assisted functional minimally invasive esophagectomy (RAFMIE). This study was approved by the Clinical Ethics Committee of Jining Medical College, China. All patients involved in the study have signed informed consent to participate in the study and consent to publication. All patients had undergone enhanced chest and abdominal computed tomography (CT), upper gastrointestinal angiography, gastroscopy, and positron emission tomography-computed tomography (PET-CT) before the operation and were confirmed to have middle and lower esophageal cancer. All patients were enrolled according to the following criteria: [1] All patients had newly diagnosed esophageal malignancies and no history of other malignancies [2]. Patients with tumors at the first diagnosis stage or in the descending stage after neoadjuvant therapy were at stage II (UICC eighth edition) or earlier, and a three-incision radical resection of esophageal carcinoma was approved after multidisciplinary consultation [3]. The patient had no prior history of thoracic and abdominal surgery and was able to tolerate the surgery with cardiopulmonary function [4]. All patients were informed in detail about the differences between RAFMIE and traditional endoscopic FMIE and voluntarily chose whether to undergo RAFMIE and signed informed consent. To ensure consistency among surgeons, all participating surgeons have extensive clinical experience with FMIE and have completed the learning curve of the robot-assisted surgical system. system [7].

Surgeons

The surgeons involved in RAFMIE in this study have rich experience in thoracoscopic surgery, have passed the RASS training(more than 50 simulated surgeries) and obtained the qualification certificate, and have undergone the clinical operation adaptation period (more than 10 RAFMIE surgeries) [8]. All the surgeons are proficient in RASS and deal with various emergency situations.

Operation technique

Following successful general anesthesia and endotracheal single-chamber intubation, patients were placed in the left lateral decubitus position. All patients underwent fully minimally invasive McKeown esophagectomy and three-field lymphadenectomy, the surgical procedures for FMIE are described in detail in our previous publications [5]. FMIE needs repair the mediastinal pleura, preserving the strange arch, vagus nerve and its pulmonary branches and bronchial arteries.The robot-assisted experimental group used the da Vinci surgical assistance system, comprising the surgeon's console, bedside robotic arm system, and imaging system, and completed thoracic and abdominal operations using three robotic arms (Fig. 1).

Data collection

Perioperative data, including gender, age, tumor location, preoperative neoadjuvant therapy, operation time, intraoperative hemorrhage, postoperative hospital stay, postoperative complication rate, and pathological results, were collected for all enrolled patients. Operation time was subdivided into five parts (Fig. 2): chest instrument connection time(T1), chest operation time(T2), chest instrument disassembly time + chest closing time + adjusting body position + abdominal instrument connection time(T3), abdominal operation time(T4), and time for neck anastomosis(T5). Postoperative complications encompassed pulmonary infection, esophagogastric anastomotic fistula, cardiac complications, chylothorax, hoarseness, incision infection, postoperative hemorrhage, among others. Postoperative follow-up was conducted at 1 month and6 months.

Statistical analysis

In order to reduce the confounding factors in the study as much as possible, a multivariate Logistic regression model was used to construct a propensity score matching (PSM). The acceptance of robot assistance was taken as the dependent variable, and the selected confounding variables were included in the model as independent variables, such as the age, gender, BMI index, smoking history, and underlying diseases (such as hypertension, coronary heart disease, diabetes, etc.). Data cleaning was performed on all included variables, missing values and outliers were handled to ensure data quality. The nearest neighbor matching method was used for one-to-one PSM, and the matching caliper was set to 0.02. All P values were 2-sided 95% CI. All statistical analyses were

Fig. 1 RASS has 4 robotic arms, but we only use 3 robotic arms to complete the operation. The figure shows the placement and angle of the robotic arms

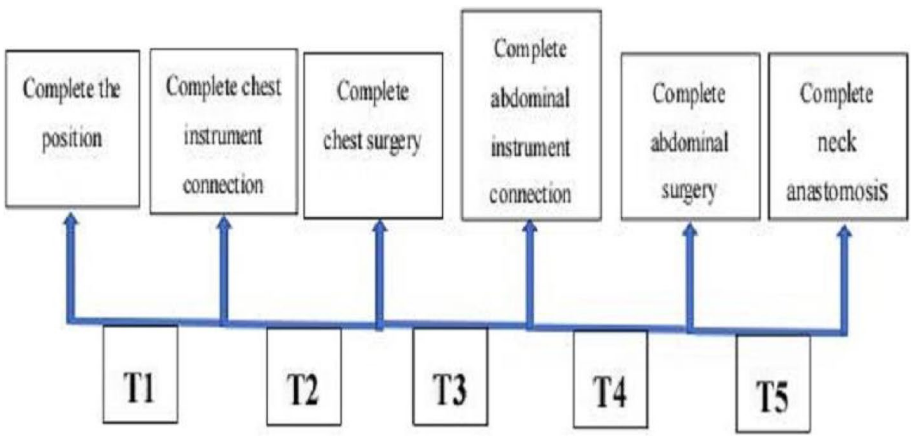

Fig. 2 Surgical time division criteria. T1:chest instrument connection time, T2:chest operation time, T3:chest instrument disassembly time + chest closing time + adjusting body position + abdominal instrument connection time, T4:abdominal operation time, T5:neck anastomosis time

performed using SPSS 24 software (IBM Corp, Armonk, NY).

Results

A retrospective analysis was performed on all patients with esophageal cancer in our hospital from September 2022 to February 2024, excluding those who had prior surgical history and refused surgery. A total of 110 patients met the enrollment criteria, including 44 RAFMIE and 66 FMIE, 40 pairs of data were successfully matched by PSM.The demographic and clinical characteristics of the two groups were not significantly different at baseline (Table 1). Most of the tumors were located in the middle esophagus(in 60 of 110 patients), and most of the pathological types were squamous cell carcinoma (in 102 of 110 patients).

Intraoperative Outcomes.

Although the instrument assembly time was longer in the RAFMIE group(3.13 ± 0.33 vs 4.15 ± 0.70 min;10.05 ± 0.64 vs 14.20 ± 0.97 min, $P <$ 0.001), the total mean operation time was shorter in the RAFMIE(222.67 ± 39.53 vs 248.28 ± 34.95 min, $P =$ 0.003), thoracic operation time (75.35 ± 20.03 vs 89.60 ± 21.88 min, $P =$ 0.005), abdominal operation time (52.25 ± 14.61 vs 71.30 ± 12.77 min, $P <$ 0.001). Both groups were equal regarding intraoperative blood loss (87.00 ± 59.85 vs 111.25 ± 72.19 ml, $P =$ 0.368), radical resection (R0) rate (95.00% vs 100.00%, $P =$ 0.156) and total lymph node yield (24.65 ± 8.88 vs 20.53 ± 9.75, $P =$ 0.047). Extubation time(6.33 ± 2.12 vs 7.78 ± 5.90,

Table 1 Baseline Demographic and Clinical Characteristics

Parameter	Before matching	*P* Value	After matching	*P* Value
FMIE	*n* = 66		*n* = 40	
RAFMIE	*n* = 44		*n* = 40	
Age (years)		0.081		0.982
FMIE	69.61 ± 6.55		67.97 ± 6.08	
RAFMIE	67.50 ± 4.00		67.95 ± 3.82	
Gender [n (%)]	Male	0.167	Male	0.796
FMIE	48 (72.73%)		31 (77.50%)	
RAFMIE	34 (77.27%)		30 (75.00%)	
BMI (kg/m2)		0.645		0.736
FMIE	26.11 ± 0.65		26.10 ± 0.47	
RAFMIE	26.05 ± 0.67		26.10 ± 0.53	
ASA score [n (%)]		0.005		1.000
FMIE				
ASA1	0 (0%)		0(0%)	
ASA2	53 (80.3%)		31 (77.5%)	
ASA3	13 (19.7%)		9 (22.5%)	
ASA4	0 (0%)		0 (0%)	
RAFMIE				
ASA1	0 (0%)		0 (0%)	
ASA2	35 (79.5%%)		31 (77.5%)	
ASA3	9 (20.5%)		9 (22.5%)	
ASA4	0 (0%)		0 (0%)	
Smoking [n (%)]	Yes	0.627	Yes	0.812
FMIE	43 (63.64)		27 (67.50%)	
RAFMIE	31 (68.18%)		28 (70.00%)	
Neoadjuvanttherapy [n (%)]	Yes	0.809	Yes	0.649
FMIE	23 (34.85%)		16 (40.00%)	
RAFMIE	15 (34.09%)		14 (35.00%)	
Comorbidity [n (%)]		0.780		1.000
FMIE	15 (22.73%)		9 (22.50%)	
hypertension	6		4	
coronary heart disease	7		4	
diabetes mellitus	1		0	
others	1		1	
RAFMIE	9 (20.45%)		9 (22.50%)	
hypertension	4		4	
coronary heart disease	4		3	
diabetes mellitus	1		1	
others	0		1	
Length of tumor(cm)		0.389		0.455
FMIE	5.01 ± 2.01		4.90 ± 1.95	
RAFMIE	4.66 ± 2.25		4.55 ± 2.22	

Table 1 (continued)

Parameter	Before matching	*P* Value	After matching	*P* Value
Tumor location [n (%)]		0.533		0.228
FMIE				
upper	2 (3.03%)		2 (5.00%)	
middle	35 (53.03%)		20 (50.00%)	
lower	29 (43.94%)		18 (45.00%)	
RAFMIE			40	
upper	2 (4.55%)		1 (4.55%)	
middle	25 (56.82%)		24 (56.82%)	
Lower	17 (38.64%)		15 (38.64%)	
Pathological pattern[n (%)]		0.535		0.302
FMIE				
squamous carcinoma	62 (93.94)		39 (97.50%)	
adenocarcinoma	3 (4.55%)		1 (2.50%)	
mucoepidermoid	1 (1.52%)		0 (0%)	
high-gradeintraepithelial	0 (0%)		0 (0%)	
RAFMIE				
squamous carcinoma	40 (90.91%)		37 (92.5%)	
adenocarcinoma	3 (6.82%)		2 (5.00%)	
mucoepidermoid	0(0%)		0 (0%)	
high-gradeintraepithelial	1 (2.27%)		1 (2.50%)	
cT-status		0.791		0.631
FMIE				
cT1	10 (15.15%)		8 (20.00%)	
cT2	26 (39.40%)		12 (30.00%)	
cT3	30 (45.45%)		20 (50.00%)	
cT4	0 (0%)		0 (0%)	
RAFMIE				
cT1	12 (27.27%)		11 (27.50%)	
cT2	10 (22.73%)		10 (25.00%)	
cT3	22 (50.00%)		19 (47.50%)	
cT4	0 (0%)		0 (0%)	
cN-status		0.916		0.907
FMIE				
cN0	26 (39.39%)		14 (35.00%)	
cN1	31 (46.97%)		24 (60.00%)	
cN2	9 (13.64%)		2 (5.00%)	
cN3	0		0	
RAFMIE				
cN0	20 (45.45%)		18 (45.00%)	
cN1	15 (34.09%)		15 (37.50%)	
cN2	9 (20.45%)		7 (17.50%)	
cN3	0		0	
Pathologic stage[n (%)]		0.892		0.837

Table 1 (continued)

Parameter	Before matching	*P* Value	After matching	*P* Value
FMIE				
I	11 (16.67%)		8 (20.00%)	
II	25 (37.88%)		12 (30.00%)	
III	28 (42.42%)		19 (47.50%)	
IV	2 (3.03%)		1 (2.50%)	
RAFMIE				
I	12 (27.27%)		12 (30.00%)	
II	10 (22.73%)		8 (20.00%)	
III	19 (43.18%)		17 (42.50%)	
IV	3 (6.82%)		3 (7.50%)	

Plus-minus values are means ± SD. *RAFMIE* Robot-assisted functional minimally invasive esophagectomy, *FMIE* Functional minimally invasive esophagectomy, *BMI* Body mass index, *ASA* American Society of Anesthesiologists

Table 2 Perioperative clinical data of FMIE and RAFMIE after propensity score matching

FMIE (*n* = 40)		RAFMIE (*n* = 40)	*P* Value
Operative time (minutes)			
TT	248.28 ± 34.95	222.67 ± 39.53	0.003
T1	3.13 ± 0.33	4.15 ± 0.70	< 0.001
T2	89.60 ± 21.88	75.35 ± 20.03	0.005
T3	10.05 ± 0.64	14.20 ± 0.97	< 0.001
T4	71.30 ± 12.77	52.25 ± 14.61	< 0.001
T5	74.20 ± 5.12	76.75 ± 10.18	0.161
Peroperative bleeding(mL)	111.25 ± 72.19	87.00 ± 59.85	0.368
Conversion to thoracotomy[n (%)]	0	0	/
Radicality of surgery [n (%)]			
R0	38 (95.00%)	40 (100%)	0.156
Number of lymph nodes [n (%)]	20.53 ± 9.75	24.65 ± 8.88	0.047
Extubation time (days)	7.78 ± 5.90	6.33 ± 2.12	0.148
Postoperative hospital stay (days)	10.85 ± 6.16	9.15 ± 2.15	0.103

Plus-minus values are means ± SD. *RAFMIE* Robot-assisted functional minimally invasive esophagectomy, *FMIE* Functional minimally invasive esophagectomy, *TT* Total operation time, *T1* Chest instrument connection time, *T2* Chest operation time, *T3* Chest instrument disassembly time + chest closing time + adjusting body position + abdominal instrument connection time, *T4* Abdominal operation time, *T5* Instrument disassembly time for neck anastomosis, *R0* Complete resection of tumor

$P = 0.148$), postoperative hospital stay (9.15 ± 2.15 vs 10.85 ± 6.16, $P = 0.103$), none of the patients switched to thoracotomy (Table 2). Some continuous outcome variables represented as box plots (Fig. 3).

Postoperative complications and follow-up

Statistically, there was no significant difference in the incidence of postoperative complications between the two groups(25.76% vs 15.00%, $P = 0.269$), anastomotic fistula(2.50 vs 7.50%, $P = 0.311$), anastomotic stenosis(2.50% vs 0%, $P = 0.320$), Pulmonary complications(15.00% vs 22.50%, $P = 0.397$),but no recurrent laryngeal nerve injury occurred or chylothorax in the RAFMIE group(0% vs 2.50%, $P = 0.320$); In addition, There was no significant difference in the mortality rate one month and the recurrence rate six months (Table 3).

Discussion

With the widespread popularization of thoracoscopic technology, MIE has emerged as the primary approach for minimally invasive treatment of esophageal cancer. In comparison with traditional open esophagectomy, it boasts significant advantages such as a larger lymph node dissection area, less bleeding, fewer postoperative complications, and better postoperative recovery [9, 10]. Of course, MIE has been continuously refined, and our team has proposed the concept of FMIE, a sophisticated surgical technique that involves preserving the mediastinal pleura, azygos arch, vagus nerve, pulmonary branches, and bronchial arteries, and has confirmed its feasibility [5]. The advent of robot-assisted surgery systems has further propelled the development of surgical methods [11–13], which have been proven to offer a superior surgical field of view, more convenient and thorough lymph node dissection, and a greater degree of minimally invasiveness [14].

Previous studies have affirmed that compared with traditional MIE, RAMIE has the advantages of shorter

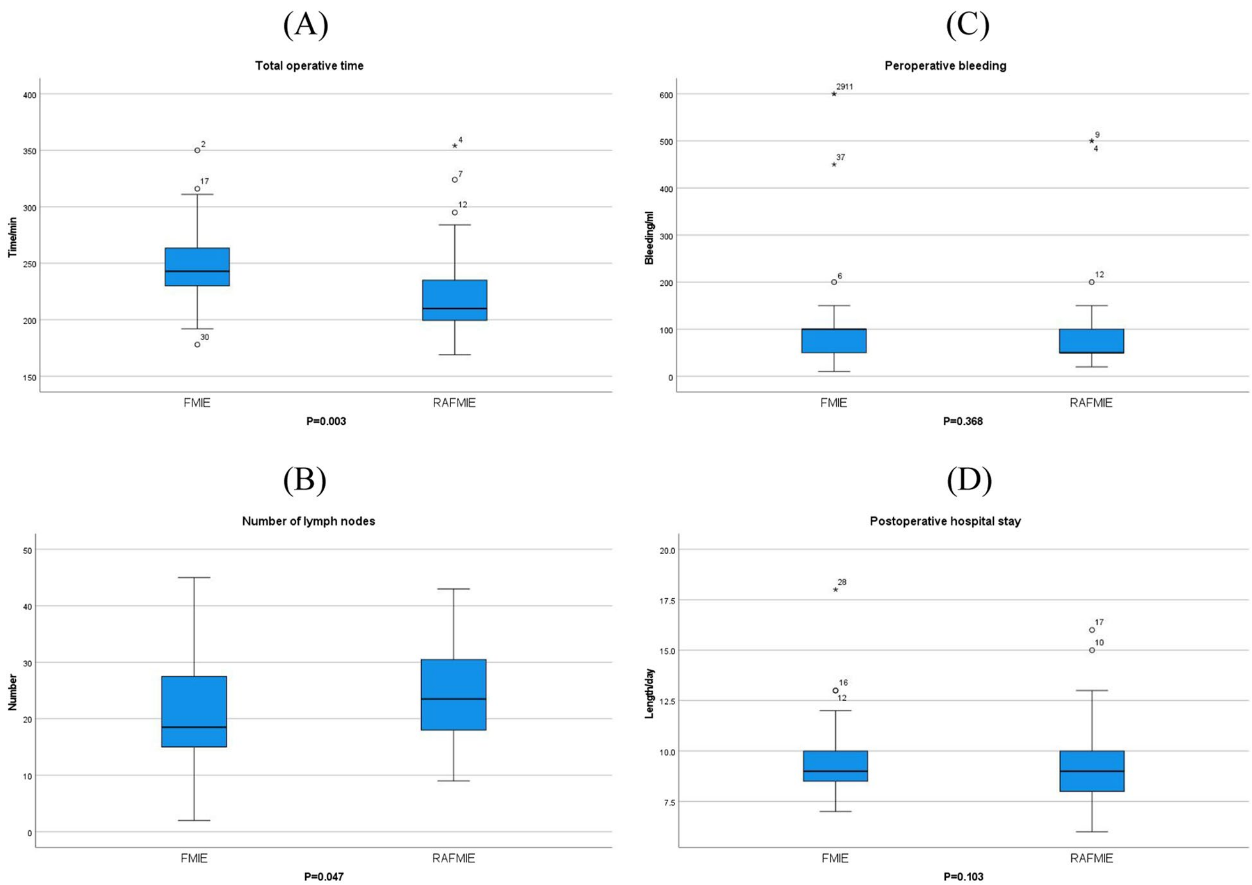

Fig. 3 Box plots for continuous outcome parameters:Signifcant differences were found for total operative time (**A**) and number of lymph nodes (**B**). Box plots for **C** Peroperative bleeding, **D** Postoperative hospital stay

Table 3 Postoperative complications and follow-up after propensity score matching

FMIE (*n* = 40)	RAFMIE (*n* = 40)		*P* Value
Total complications [n (%)]	10 (25.76%)	6 (15.00%)	0.269
Anastomotic fistula [n (%)]	3 (7.50%)	1 (2.50%)	0.311
Anastomotic stenosis [n (%)]	1 (2.50%)	0 (0%)	0.320
Pulmonary complications [n (%)]	9 (22.50%)	6 (15.00%)	0.397
pneumonia	4 (10.00%)	3 (7.50%)	0.697
pleural effusion	4 (10.00%)	3 (7.50%)	0.697
Respiratory failure	1 (2.50%)	0 (0%)	0.320
Gastrointestinal bleeding [n (%)]	1 (2.50%)	0 (0%)	0.320
Chylothorax [n (%)]	1 (2.50%)	0 (0%)	0.320
Recurrent laryngeal nerve injury[n (%)]	1 (2.50%)	0 (0%)	0.320
Wound infection [n (%)]	3 (7.50%)	1 (2.50%)	0.311
In-hospital mortality [n (%)]	0 (0%)	0 (0%)	/
d mortality [n (%)]	0 (0%)	0 (0%)	/
180-d recurrence [n (%)]	1 (2.50%)	0 (0%)	0.320

operation time, better dissection of thoracic and abdominal lymph nodes, and a lower incidence of postoperative complications [15]. FMIE requires the preservation of the mediastinal pleura, azygos arch, vagus nerve, pulmonary branch, and bronchial artery, which imposes higher technical demands on clinicians. Previous studies have discovered that robot-assisted systems possess excellent stability and operability [13, 16]. Therefore, we put forward a hypothesis: the RASS, relying on its stable and flexible robotic arm and good field of view, can help surgeons better perform FMIE, shorten the operation time, and reduce surgical complications. Through the collection of perioperative data and short-term follow-up data of patients in both groups, we have preliminarily demonstrated that the RASS can reduce operation time, mainly in the chest and abdomen.

Some previous studies found that robot-assisted surgery system could not significantly shorten the operation time of esophageal cancer, which might be related to the proficiency of surgeons in operating robot-assisted surgery system. In our study, all of the surgeons performing RAFMIE completed the learning curve of the robot-assisted surgery system and were certified to ensure the objectivity [17]. Our research found that the robotic arms needed separate angle adjustment and aseptic protection, so RAFMIE did take longer to connect the instrument than FMIE, and the time gap was more significant when changing positions during the operation. The robot-assisted surgical system, with excellent surgical field of view and stable and flexible robotic arms, significantly reduces the operation time of the chest and abdomen, resulting in a shorter total surgical time of the RAFMIE than the FMIE. There were no significant differences between the two groups in tumor location (mainly middle esophageal carcinoma), pathological type (mainly squamous cell carcinoma), pathological stage, and resection rate of R0. However, RAFMIE was more advantageous in lymph node dissection, which was consistent with some previous conclusions [18–20].

Due to the lack of contact force feedback, the safety of robot-assisted surgery system has been questioned, but our study found no significant differences between the two groups in terms of hemorrhage, postoperative pulmonary complications, chylothorax, anastomotic fistula, anastomotic stenosis, recurrent laryngeal nerve injury, wound infection, mortality 1 month and tumor recurrence 6 months. Through our study, the application of robot-assisted surgery system to FMIE is safe, reliable and effective. It is worth noting that no recurrent laryngeal nerve injury occurred in RAFMIE, which may be related to the insufficient sample size, in addition, all surgeons reported that the robot-assisted surgical system had a clearer field of view and a more flexible angle during lymph node dissection, so we propose a hypothesis: Robot-assisted surgical systems have advantages in protecting the recurrent laryngeal nerve. This requires further data collection and research.

There are several limitations to our method that should be addressed. First of all, this study is a single-center retrospective study, which cannot guarantee the same sample size of the two subgroups. However, the sample size of this study is limited, and the proportion of neoadjuvant therapy is low, so this study does not compare the cases who received neoadjuvant therapy alone, which limits the external validity and universality of this article and requires us to further study. At the same time, there is also heterogeneity in perioperative data collection, which may lead to inaccurate data. Second, the learning curve is also an important limitation, and RASS has a long learning curve. The surgeons involved in RAFMIE in this paper have passed the systematic training, obtained the certificate, and gone through the operation adaptation period, but there are still inevitable technical differences. At the same time, RASS is expensive, which is not conducive to the promotion of primary hospitals. Third, patients with a prior history of chest and abdominal surgery were not included in the study, so whether RASS can still shorten the operation time in such patients needs further study. However, according to our preliminary findings, RASS may have greater advantages in the treatment of patients with secondary or multiple operations, which will be introduced in subsequent reports.

Conclusions

In this randomized controlled trial, our results show that RAFMIE is safe and effective in the treatment of esophageal cancer even without touch feedback. Compared with FMIE, RAFMIE significantly shortens the operation time, has obvious advantages in lymph node dissection, and is worth further research in the protection of recurrent laryngeal nerve and the reduction of postoperative pneumonia and other complications. Future follow-up of the trial may clarify the long-term benefits as far as lymph node dissection is concerned.

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Authors' contributions

Yutao Wei, Honghao Fu and Xiaoyu Lv designed the research; Yutao Wei, Honghao Fu, Zhi Li performed the thoracoscopy; Xiaoyu Lv, Zhi Li and Honghao Fu collected the data and wrote the whole paper. Zhi Li is co-first author, Honghao Fu is the co-corresponding author. All authors reviewed the manuscript.

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None.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Our study was approved by the Clinical Ethics Committee of Jining Medical College, China. All patients involved in the study have signed informed consent to participate in the study and consent to publication.

Competing interest

The authors declare no competing interests.

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