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Efficacy of robot-assisted thoracoscopic surgery in the treatment of pulmonary sequestration in children

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ABSTRACT

Objective This study was performed to evaluate the efficacy of robot-assisted thoracoscopic surgery (RATS) in the treatment of pulmonary sequestration (PS) in children.
Methods All video-assisted thoracoscopic surgery (VATS) and RAST performed on patients with PS at a single center from May 2019 to July 2023 were identified. The χ^2 and Wilcoxon tests were used to compare the perioperative outcomes between VATS and RATS groups.
Results Ninety-three patients underwent RATS while 77 patients underwent VATS. In both two groups, one patient converted to thoracotomy and no surgical mortality case. The median operation time was longer for the RATS group compared with the VATS group (75 min *vs.* 60 min, p <0.001). A lower ratio of chest tube indwelling (61.3% *vs.* 90.9%, p <0.001), fewer drainage days (1.0 day *vs.* 2.0 days, p <0.001), and a shorter postoperative length of stay (5.0 days *vs.* 6.0 days, p <0.001) were found in the RATS group than that in the VATS group. No significant difference was found in the incidence of short-term postoperative complications (hydrothorax and pneumothorax) between two groups.
Conclusions RATS was safe and effective in children with PS over 6 months old and more than 7 kg. Furthermore, RATS led to better short-time postoperative outcome than VATS. Multi-institutional studies are warranted to compare differences in long-term outcomes between RATS and VATS.

INTRODUCTION

Pulmonary sequestration (PS) is a congenital malformation first reported by Pryce in 1946,[1] where non-functional lung parenchyma with anomalous arterial supply is formed and isolated from the normal bronchial tree. Based on the visceral pleura at the border of normal lung tissue, PS can be divided into intralobar PS (ILS) and extralobar PS (ELS). In rare cases, ELS can be found in the inner part of the diaphragm, abdomen, neck, and mediastinum.[2] It may result in recurrent infections or, less likely, hemoptysis at late childhood or early adulthood if untreated. Complete surgical resection is the treatment of choice for any type of PS. The main surgical concern is managing aberrant vessels, which can cause disastrous bleeding if not handled properly. The traditional approach by thoracotomy has been successfully replaced by video-assisted thoracoscopic surgery (VATS).[3] However, there are unique technical challenges associated with VATS, such as two-dimensional images and rigid, straight instruments, which hinder its adoption in certain situations.[4] The three-dimensional view with depth perception in da Vinci robot system provides images with increased resolution, a significant improvement over the conventional thoracoscopic camera which enabled surgeons to perform safer and more precise dissections of aberrant vessels and sequestered tissue.

Robot-assisted thoracoscopic surgery (RATS) has been successfully performed with encouraging results in the management of various thoracic pathologies, especially in adult surgery. Due to the relatively late application of RATS in the field of pediatrics, the number of pediatric cases is far less than that in adults. Both VATS and RATS are recently recognized as safe and effective methods for pulmonary resection even in children.[5 6] However, there is a scarcity of valid evidence with a large sample of cases to evaluate the efficacy of the robotic surgical methods in treatment of PS. Overall, evidence of outcomes from RATS and VATS in children is limited with mainly case series. The current study was designed to evaluate the efficacy of RATS in children with PS and to perform a short-term comparison of perioperative outcomes after RAST and VAST in treating PS in pediatric patients.

METHODS

Study design and population

All consecutive pediatric patients with PS who underwent thoracoscopic surgery at our center from May 2019 to July 2023 were retrospectively identified. Clinical diagnosis was made based on the radiological appearance of enhanced CT that anomalous arterial supply via the thoracic aorta or abdominal aorta was detected before surgery as well as pathological results of resected specimen after surgery. Patients with PS located in the diaphragm or extrathoracic cavity were excluded. Patients were separated into two groups: those who underwent RATS or VATS. All surgical procedures were conducted by the same senior surgeon to ensure uniformity.

RATS versus VATS procedures

Anesthesia and patient position

Single-lung ventilation was achieved using selective endobronchial intubation or a bronchial blocker, which was also conducted in the VATS procedures. The patient was placed in a maximally flexed lateral decubitus position with upper limb flexion on the side of the head (figure 1A).

Docking and robot system position

All patients underwent surgery using the da Vinci Xi Robotic System (Intuitive Surgical, California, USA). CO_2 inflation was applied at 6 mmHg. The docking was as follows:

1. The first incision (camera arm): the eighth intercostal space (ICS) at posterior axillary line.
2. The second incision (anterior arm): the sixth ICS at the middle clavicle line.
3. The third incision (posterior arm): the eighth ICS at the subscapular line, ensuring that there was a sufficient distance (5–8 cm) between the anterior and posterior arm holes.

A 30-degree scope was introduced through an 8 mm trocar and secured to the camera arm, allowing the positioning of the other instruments to be accomplished under direct vision. In addition, an auxiliary incision (5 mm trocar) was placed in the seventh ICS at the anterior-middle axillary line for suction or gauze. The 5 mm incision was extended to accommodate a 12 mm trocar when endoscopic staplers were needed. The assistant stood on the abdominal side of the patient. The da Vinci robot located at the back of the patient's head was approached and docked (figure 1B).

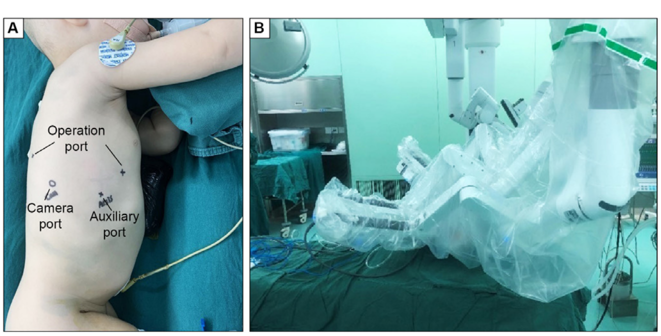

Figure 1 Preoperative procedure: (A) patient position and port placement; (B) robotic docking.

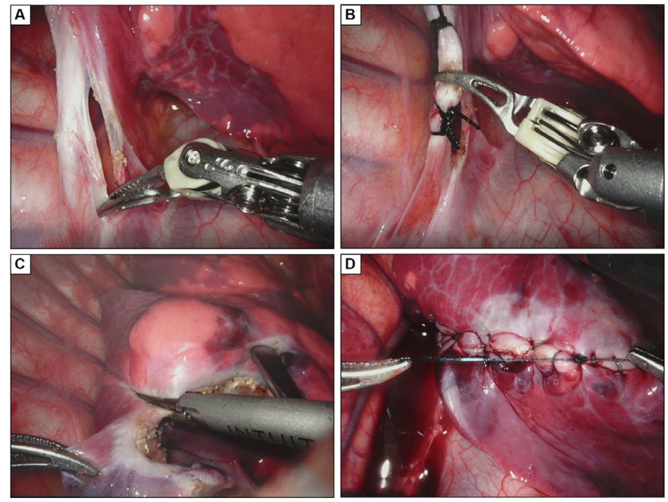

Figure 2 Robotic surgical procedure in intralobar pulmonary sequestration (ILS): (A) dissecting the aberrant artery; (B) ligating and cutting the aberrant artery; (C) resecting the ILS lesion by Harmonic ACE curved shears; (D) suturing the surface of the wound.

RATS surgical procedure

The right arm of the robot was connected to the Maryland bipolar cautery dissector (Intuitive Surgical), while the left arm was connected to the atraumatic grasper (Cadiere forceps; Intuitive Surgical). The aberrant artery was ligated with silk suture and vascular clips (figure 2A-B) (Hem-o-lok Weck Surgical Instrument; Teleflex Medical, Durham, North Carolina, USA) . ELS was resected directly, a procedure known as sequestrectomy. Lobectomy or partial lobectomy (wedge resection and segmental resection) was performed depending on the size and location of the ILS by Harmonic ACE curved shears (Intuitive Surgical) or endoscopic staplers (figure 2C). If the ILS lesion was wide in size, leaving minimal normal lung tissue or was close to the hilus pulmonis, lobectomy was performed. If the ILS lesion was mainly confined to a single segment, segmental resection was performed. Otherwise, a simple wedge resection was performed if the ILS lesion was relatively small. The decision to place a chest tube was dependent on the intraoperative condition. Finally, tension-reduction sutures were performed layer by layer on the fascia and subcutaneous layers, then skin glue was used to bond the incision instead of intermittent sutures (figure 2D).

VATS procedure

Four 5 mm ports were used and placed similarly to those in the RATS group. Dissection was performed using the electrocoagulation hook or the Harmonic system (Ethicon Endo-Surgery, USA). The procedures for aberrant arteries and lesions were similar to those in RATS.

Postoperative management

Patients in the two groups received the same postoperative treatment in the thoracic surgery ward. Chest tubes were selectively placed for patients with extensive residual

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lung surface wounds, severe injuries of lymphatic vessels, or small pulmonary vessels after operation. Drainage tubes were removed when the output was less than 50 mL over a 24-hour period and there was no air leak. A chest X-ray was taken before discharge. Discharge criteria included drainage tube removal, a normal postoperative chest X-ray and wound healing.

Collected data and outcomes

Demographic, clinical, and short-term postoperative outcome characteristics between patients who underwent RATS or VATS were compared. The short-term outcomes included the ratio of chest tube indwelling, chest drainage time, postoperative length of stay, and morbidity of postoperative complications.

Statistical analysis

Statistical analysis was performed using SPSS V.25 software. All quantitative data were non-normally distributed and presented as the median with the interquartile range (IQR). Categorical data were presented as number (percentage). Comparisons between the two groups were performed using the χ^2 test for qualitative data and the Wilcoxon test for quantitative data. All tests were two tailed and *p* value of less than 0.05 was considered statistically significant.

RESULTS

Perioperative conditions

Of the 170 children who met the inclusion criteria, 93 (54.71%) patients underwent RATS, while 77 (45.29%) patients underwent VATS. Demographics and preoperative characteristics in two groups were comparable (table 1). The operation time of RATS group was significantly longer than that of VATS group, and this finding was consistent in the sequestrectomy, segmental resection and lobectomy subgroups. There was no surgical mortality case in both two groups and one case in each group required conversion to thoracotomy (1.08% *vs.* 1.30%, *p*=1.000).

Short-term postoperative outcomes of patients in RATS versus VATS group

The proportion of patients requiring chest tube indwelling was significantly lower in the RATS group compared with the VATS group (61.3% *vs.* 90.9%, *p* <0.001). Furthermore, patients undergoing RATS

Table 1 Patient demographics and perioperative characteristics

Parameter	RATS group (*n*=93)	VATS group (*n*=77)	X^2/z value	*P* value
Age (months), median (IQR)	10.0 (7.0, 25.0)	9.5 (7.0, 17.5)	0.843	0.399
Weight (kg), median (IQR)	9.5 (8.5, 13.1)	9.2 (8.3, 12.0)	0.592	0.554
Gender, *n* (%)			0.320	0.571
Male	54 (58.1)	48 (62.3)		
Female	39 (41.9)	29 (37.7)		
Site, *n* (%)			0.041	0.840
Left	59 (63.4)	50 (64.9)		
Right	34 (36.6)	27 (35.1)		
Type, *n* (%)			0.032	0.858
ILS	64 (68.8)	52 (67.5)		
ELS	29 (31.2)	25 (32.5)		
Operative pattern, *n* (%)			0.894	0.640
Sequestrectomy	29 (31.2)	25 (32.5)		
Segmental resection	47 (50.5)	42 (54.5)		
Lobectomy	17 (18.3)	10 (13.0)		
Preoperative infection, *n* (%)*	14 (15.1)	20 (26.0)	3.140	0.076
Total operative time (min), median (IQR)	75.0 (60.0, 92.5)	60.0 (40.0, 70.0)	4.511	<0.001
Sequestrectomy	60.0 (50.0, 72.5)	40.0 (30.0, 60.0)	3.275	0.001
Segmental resection	75.0 (65.0, 90.0)	60.0 (53.8, 76.3)	2.849	0.004
Lobectomy	120.0 (90.0, 150.0)	70.0 (60.0, 105.0)	2.627	0.009
Conversion, *n* (%)	1 (1.1)	1 (1.3)	–	1.000

A *p* value <0.05 was considered statistically significant.
*At least one pulmonary infection before operation.
ELS, extralobar pulmonary sequestration; ILS, intralobar pulmonary sequestration; IQR, interquartile range; RATS, robot-assisted thoracoscopic surgery; VATS, video-assisted thoracoscopic surgery.

Table 2 Short-term postoperative outcomes in RATS and VATS

Variables	RATS group (*n*=93)	VATS group (*n*=77)	X^2/*z* value	*P* value
Chest tube indwelling, *n* (%)	57 (61.3)	70 (90.9)	19.556	<0.001
Chest drainage time (days), median (IQR)	1.0 (0.0, 1.0)	2.0 (1.0, 3.0)	5.882	<0.001
Postoperative length of stay (days), median (IQR)	5 (4.0, 6.0)	6 (5.0, 7.0)	3.590	<0.001
Postoperative complication, *n* (%)				
Hydrothorax	22 (23.7)	10 (13.0)	3.138	0.076
Pneumothorax	6 (6.5)	6 (7.8)	0.115	0.734

A *p* value <0.05 was considered statistically significant.
IQR, interquartile range; RATS, robot-assisted thoracoscopic surgery; VATS, video-assisted thoracoscopic surgery.

surgery had shorter drainage days (2.0 days *vs.* 1.0 day, *p* <0.001) and postoperative length of stay (5.0 days *vs.* 6.0 days, *p* <0.001). There was no significant difference in the incidence of postoperative complications between the two groups (table 2).

DISCUSSION

In our recent study, RATS were performed in 93 children with PS over 6 months old and more than 7.0 kg. RATS was a safe and feasible approach with notable short-time postoperative outcome than which in VATS.

RATS started relatively late in the field of pediatrics, and the number of operations carried out in children is much lower than in adults. Navarrete Arellano and Garibay González reported 6 cases of RATS from 2015 to 2018, including 3 cases of diaphragm folding, 2 cases of lobectomy, and 1 case of bronchial cyst resection.[7] Durand *et al.* reported seven cases of robotic lobectomy for bronchiectasis in children.[8] Meehan and Sandler documented 11 cases of RATS, including 4 cases of lung surgery, with only 1 case involving ILS.[9] The present study confirmed the efficacy of RATS in children with PS.

To date, there is no global consensus on the choice of the minimum age for RATS. The use of robotic systems needs a certain amount of space between the arms (typically 8 cm), which may limit patients who are too young. Denning *et al.* noted that the size of robotic instruments could be prohibitively large for the ICS of a child weighing 5 kg or less.[10] Molinaro *et al.* conducted a retrospective analysis of RATS and considered a weight above 7.0 kg to be appropriate for RATS.[11] Ballouhey *et al.* reported two cases with esophageal atresia (weight 3.0 and 3.1 kg, respectively) performed RATS; however, eventually they were converted to thoracotomy.[12] Meehan *et al.* performed four cases of robot-assisted lobectomy in infants with congenital cystic adenomatoid malformation or PS.[4 9] The average age of these infants was 7 months, with an average body weight of 7.9 kg. They also planned to perform RATS on a newborn weighing 2.5 kg with diaphragmatic hernia but opted for VATS due to the small size of chest.[9] Our study established criteria for RATS as being over 6 months old and having a minimum weight of 7.0 kg. Furthermore, there is currently no international consensus regarding the optimal age for surgery for PS. Children with asymptomatic sequestration are particularly susceptible to developing pulmonary infections and abscesses, especially with ILS.[13] As the infection rate of PS significantly increased with age, performing surgery becomes more challenging, resulting in longer operative time, increased intraoperative bleeding, and extended hospital stays. Given that most complications manifest within the first year of life, 6 and 12 months of age became to be a preferred range of age.[2 14 15]

Compared with the more flexible approach for the placement of a 5 mm trocar in VATS, RATS requires stricter discipline for each port and docking. The da Vinci surgical system recommends that the distance between each trocar should be approximately 8 cm. However, based on reported experiences by Ballouhey *et al.*, a distance of approximately 5 cm is also feasible.[16] The robotic port placement was adjusted based on the operation experience, ensuring that each arm would not interfere with the small chest. The overall arrangement was fan shaped, similar to the adult procedure.[17] Durand *et al.* also reported a 'W modified' shape.[8] In addition, there is a very special type of ELS, in which the PS is located in the diaphragm. In that case, the placement of the four ports is quite different from the usual procedure which was described in our previous reports.[18] The assistant stood at the head side of the patient. The robot located at the back side of the patient's abdomen. The diaphragm was dissected to explore the tissue of PS. After the intradiaphragmatic lesion was removed, the diaphragm was sutured to prevent iatrogenic diaphragmatic hernia. We had previously reported 10 cases of intradiaphragmatic ELS treated by RATS,[18] which were not included in this study.

The conversion rate of robotic lobectomy was 4.7%–9.2% in adults, with the main reasons being bleeding and adhesion. Due to anatomical reasons, the conversion rate of upper lobectomy was relatively high, up to 17.5%.[19–21] Although the conversion rate of robotic lobectomy in adults was reported to be lower than that of VATS,[22] no significant difference in ratio of conversion between the two groups and no surgical death in either group were shown in our study, indicating the safety of the RATS was similar with VATS. Previous studies showed that the overall conversion rate of robotic surgery in pediatric patients is 2.5%–4.7%, regardless of the operative site.[7 23] Moreover, Cundy *et al*. showed that the conversion rate of robotic thoracic surgery in children was approximately 10%.[23] Durand *et al*. reported on 18 children with bronchiectasis,[8] including 7 cases treated with RATS and 11 cases with VATS, and noted that there was no conversion in the RATS group and 5 in the VATS group. In our study, one surgical conversion occurred in each group and both occurred during lobectomy procedures. There was also no significant difference of conversion between the lobectomy subgroup, which may be related to the small sample size of each subgroup. In the VATS group, a 4-year-old patient with ILS suffered conversion because of severe pleural adhesion and bleeding due to preoperative recurrent infections. Although preoperative pulmonary infection was considered to be the crucial factor for conversion, we believe that effective single-lung ventilation is another important factor for both types of surgery. In the RATS group, a 7-month-old patient with ILS suffered conversion due to displacement of the bronchus blocker and failure of single-lung ventilation in the process of dissecting the bronchia. The short length of bronchi and the lack of proper bronchial blockers made it challenging to perform satisfactory single-lung ventilation in pediatric patients, especially in low-weight patients.

Among the lobectomy subgroup, the operation time was significantly longer in the RATS group than the VATS group. These results were similar to Durand *et al*.'s study in which the median operative time of lobectomy was significantly longer in RATS than in VATS (268 (221.5–286.5) min *vs*. 131 (115.5–190.0) min, p=0.004).[8] Due to the higher proportion of preoperative infections, such as infected congenital pulmonary malformations, primary ciliary dyskinesia, and postviral infections, the operation time in their study was longer than ours. In addition, we timed the installation and withdrawal procedures separately. The installation time was within 5–10 min, and the withdrawal time was within 3–5 min. Therefore, we attributed the extra time primarily to the replacement of robotic instruments during the operation. Similar evidence has shown that there is no significant difference in the pure operative time between the two groups when excluding the instrument replacement time and docking time.[24]

In our study, RATS demonstrated superior efficiency in short-time postoperative outcomes compared with VATS, including ratio of chest tube indwelling, chest tube duration, and postoperative duration. The increased df and enhanced dexterity in RATS improved the dissection of anomalous vessels and lesions as well as executing hemostasis more effectively, which may be a potential reason for the reduction of chest tube indwelling ratio and drainage duration. These findings suggest that RATS offers advantages in specific postoperative outcomes despite longer duration of operation, highlighting its potential as a favorable treatment option for pediatric patients with PS. Additionally, as a novel technology, RATS did not increase the conversion rate or postoperative short-term complications compared with VATS.

RATS also presented certain limitations, such as increased surgery cost. However, the reduction in hospitalization duration and overall nursing care costs partially offset the additional financial burden associated with implementing robotic surgery.[21] Rowe *et al*. found that robotic surgery resulted in an 11.90% reduction in direct expenses, mostly due to shorter hospitalization, and assumed that increased surgical volume and a competitive market might potentially reduce robotic surgery costs.[25] A recent study suggested that once a hospital performs 25 or more pulmonary surgeries, the costs of RATS and VATS become equivalent.[26] Concerning surgical incisions, RATS required larger incisions to accommodate an 8 mm trocar and an additional incision compared with VATS. To mitigate scar formation, tension-reduction sutures were used and no noticeable visual difference in incision length was observed between the two groups. Li *et al*. reported the scar scores showed no significant differences when assessed 3 months after operation.[24] Instruments of appropriate size for children in robotic system are expected. Recently, 3 mm-sized instruments for robotic systems have been developed which might be particularly suitable for the younger children and neonates.[27]

In this study, RATS showed better short-time postoperative outcomes compared with VATS. However, further accurate studies are needed to evaluate the long-term benefits of RATS. Furthermore, this is a single-center study by one surgeon and more multi-institutional clinical studies are warranted to explore the differences between RATS and VATS.

In conclusion, although there were limitations in the application of RATS in younger, low-weight infants, our study demonstrates that RATS is a feasible and safe approach with notable advantages in short-term postoperative outcomes for pediatric patients with PS over 6 months and more than 7 kg in weight. However, the benefits of this new technique over traditional thoracoscopic approaches need to be thoroughly assessed through further robust prospective investigations.

Contributors LL contributed to conceptualization, data collection, formal analysis and writing original draft and review. ZT, TH, YG and JZ contributed to data curation, formal analysis and data supervision. JY and JX contributed to formal analysis and data supervision. QS contributed to resources, project administration and supervision. All authors read and approved the final manuscript.

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Patient consent for publication Consent obtained from parents.

Ethics approval This study was approved by the Medical Ethics Committee of Children's Hospital, Zhejiang University School of Medicine (2022-IRB-272).

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