SURGERY FOR CONGENITAL HEART DISEASE

VIDEO-ASSISTED THORACOSCOPIC SURGERY FOR CONGENITAL HEART DISEASE

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Video-assisted endoscopic techniques have reduced operative trauma in adult thoracic and general surgery, but applications in children with congenital heart disease have been limited. We report the development of video-assisted thoracic surgery procedures for neonates and infants with cardiovascular disease. Endoscopic instruments and techniques for pediatric cardiovascular procedures were designed and tested in the animal laboratory. Forty-eight operations were subsequently performed in 46 pediatric patients ranging in age from 2 hours to 14 years (median 9 months), weighing from 575 grams to 54 kg (median 8.5 kg). Clinical applications included seven different surgical procedures: patent ductus arteriosus interruption in infants ($n = 26$) and premature neonates ($n = 5$), vascular ring division ($n = 8$), pericardial drainage and resection ($n = 3$), arterial and venous collateral interruption ($n = 2$), thoracic duct ligation ($n = 2$), epicardial pacemaker lead insertion ($n = 1$), and diagnostic thoracoscopy ($n = 1$). There was no operative mortality. Technical success, defined as a video-assisted procedure completed without incising chest wall muscle or spreading the ribs, was achieved in 39 of 48 procedures (82%), with thoracotomy required to complete nine procedures. Most patients (22/25, 88%) undergoing elective ductus ligation were extubated in the operating room and discharged from the hospital within 48 hours of the operation. Eight of the last 10 patients having ductus ligation were discharged on the first postoperative day. Residual ductal flow was assessed by (1) transesophageal echocardiography in the operating room (incidence: 0/25, 0%, 70% CL 0% to 7.3%); (2) discharge auscultation (incidence: 1/30, 3%, 70% CL 0.5% to 10.8%); and (3) follow-up Doppler echocardiography (incidence: 3/25, 12%, 70% CL 5.4% to 22.6%). Video-assisted thoracoscopic techniques can be safely applied to pediatric patients with patent ductus arteriosus and vascular rings and may become an effective addition to the staged management of more complex forms of congenital heart disease. (*J THORAC CARDIOVASC SURG* 1995;109:499-508)

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By reducing surgical trauma while enhancing visualization, video-assisted endoscopic techniques have assumed an increasing role in operations on adults.¹ The demands for improved visualization and reduced tissue trauma are also compelling in the pediatric population, where size constraints are extreme and immature tissues are vulnerable to mechanical injury. Pediatric video-assisted thoracic surgery (VATS) applications have been limited by a lack of equipment and techniques adapted to small patients. Pediatric VATS has been reported for patent ductus arteriosus (PDA) interruption² and vascular ring division,³ which have been performed successfully, with minimal morbidity. So that the applications of pediatric VATS could be extended,

endoscopic instrumentation and surgical strategies were developed to accommodate the small size and complex cardiopulmonary physiology characteristic of this patient population. This report reviews our initial experience with VATS in the animal laboratory and subsequently in 46 patients with congenital heart disease.

Methods

Animal experience

Subjects. Pediatric cardiovascular VATS applications were developed in the animal laboratory, newborn Yorkshire swine being used to approximate the size and anatomic relationships in the human neonatal pleural space. Animals were treated humanely according to guidelines established by the National Society for Medical

Table I. Pediatric VATS instruments for cardiovascular procedures

Instrument	Trocar size	Useful weight range	Company*	Cost (1993 dollars)
Videoscope 2.7 mm	2.8 mm	Under 2 kg	Dyonics	2,785
Videoscope 4 mm	4 mm	Under 40 kg	Dyonics	2,785
Camera		Under 40 kg	Dyonics	22,500
Monitor		All	Dyonics	9,800
Lung retractor	5 mm	Over 5 kg	Advanced Surgical	595
Lung retractor	4 mm	Under 5 kg	Pilling	Prototype
Grasper	2.5 mm	Under 20 kg	Dyonics	1,500
Cautery probe	4 mm	All	Pilling	40
Clip applicator		Over 5 kg	Weck	390
Clip applicator		All	Pilling	Prototype
Needle holder	4 mm	All	Pilling	Prototype
Scissors	4 mm	Under 40 kg	Dyonics	750
Trocar	2.8 and 4 mm	Under 40 kg	Pilling	250
Vascular clamp	4 mm	Under 40 kg	Pilling	Development
Angled grasper	4 mm	Under 40 kg	Pilling	Development

*Advanced Surgical, Advanced Surgical, Inc., Princeton, New Jersey; Dyonics, Smith and Nephew, Dyonics, Inc., Andover, Massachusetts; Pilling, Pilling Co., Fort Washington, Pennsylvania.

Research and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources and published by the National Institutes of Health (NIH Publication No. 86-23, revised 1985). The protocol was reviewed and approved by the Animal Care and Use Committee, Children's Hospital, Boston, Massachusetts.

Anesthesia. Anesthesia was induced with ketamine 40 mg/kg, given intramuscularly, and maintained with a mixture of halothane (0.5% to 1%) and oxygen. Animals' lungs were ventilated at 15 ml/kg with a volume-cycled ventilator at 10 to 20 breaths/min. Arterial pressure and continuous electrocardiographic tracings were monitored. Animals recovered in the animal facility and were put to death with ketamine (100 mg/kg) on postoperative day 1 for inspection of the operative sites.

Basic surgical technique and instruments. Each animal underwent PDA interruption and pericardial resection. Procedures were planned to assess technique and instrument performance in four areas: access, exposure, dissection, and hemostasis. Data recorded included procedure times, operative mortality, morbidity, postmortem dissection results, and subjective assessment of instrument performance. Current VATS instruments are listed in Table I.

Four thoracostomies were used in each procedure. Whenever possible, so that intercostal trauma could be minimized, instrument diameters were reduced to 4 mm or less for animals over 2 kg and 2.8 mm or less for those under 2 kg. Arthroscopic videoscopes with a 7 cm working length, 2.7 or 4 mm diameters, and a 30-degree face angle were coupled with cameras providing 4× magnification. Trocars allowed rapid instrument exchange, and a combination of short (1.5 cm) and long (4 cm) trocars with 2.7 or 4 mm internal diameters accommodated a wide range of chest wall thicknesses. Chest wall muscles were never incised or divided; instead, trocar placement was achieved with blunt dissection with the aid of a curved hemostat. This technique also prevented pleural tent formation,

chest wall bleeding, and lung injury. Temporary hypoven-tilation allowed safe video scope insertion.

Thoracostomy positions for each procedure were patterned to maximize exposure and minimize instrument contact. Single lung ventilation techniques were limited by tracheal size, necessitating retraction of the inflated, moving lung. Initial efforts to retract the lung with malleable coronary probes resulted in poor exposure and pulmonary parenchymal trauma. Expandable retractors, with broad surface areas, maintained their position despite underlying lung motion, and were atraumatic.

For precision, a two-handed dissection technique was adopted. Two separate ports were used to admit a 2.5 mm diameter grasper and a cautery probe. The lack of depth perception during VATS and the attendant risk of injury to underlying structures were accommodated by a modified dissection technique with an L-shaped electrocautery probe, which was used to elevate tissues away from underlying structures before the current was activated. When necessary, countertraction was achieved with stay sutures brought in through the chest wall.

Even small amounts of blood in the operative field significantly reduced visualization, so that cautery dissection was essential. PDA occlusion was accomplished with single vascular clips. Clip applicators designed for adult VATS were effective in animals over 3 kg, but instrument diameters were too large for the intercostal space in animals under 2 kg. Prototype clip applicators were tapered to minimize thoracostomy size and maintain tactile control of the closure force. This tapering was balanced against the need to supply sufficient force to achieve complete clip closure. Suction was used sparingly because it reinflated the lung and compromised exposure.

Clinical experience

Patients. All patients referred for pediatric cardiovascular VATS procedures to Children's Hospital, Boston, were included in this report, with no exclusions based on age, size, or degree of cardiopulmonary dysfunction. The

only general exclusion criterion for VATS was extensive pleural adhesions. For VATS PDA interruption, specific exclusion criteria included patients with calcified ducts (by chest roentgenograms), PDAs equal in diameter to the descending aorta, and those with transcatheter occlusion devices within the ductal lumen. During this study, all patients referred for surgical PDA closure underwent VATS, except in six cases in which open procedures were performed because of patient preference or unavailability of the VATS surgeon. For VATS vascular ring division, patients with rings composed entirely of patent vascular structures were excluded, as were patients with an aortic diverticulum compressing the airway.

Patient charts, operative reports, and intraoperative video recordings were retrospectively reviewed. Baseline clinical data included age and weight at operation, preoperative cardiac anatomy and prior cardiac surgical procedures, total operative time (defined as the time from entering to leaving the operating room), procedure time (defined as the time from incision to closure), intraoperative arterial oxygen saturation and end-tidal carbon dioxide, intraoperative transesophageal echocardiography results, need for transfusion, duration of mechanical ventilation (the time from arrival in the intensive care unit until extubation), complications, hospital stay, echocardiography, and chest x-ray results. Procedures that necessitated a thoracotomy (defined as any incision in chest wall muscle or rib spreading with a retractor) to complete the operation were considered technical failures, but not complications, if the operation was completed successfully. Follow-up telephone interviews were conducted, and results of postoperative examinations by referring physicians were obtained. Patients who had had PDA closure underwent follow-up echocardiography from 1 to 6 months after the operation.

Anesthesia. Each patient was assessed before the operation for airway size and anatomy. Patients deemed suitable for one-lung ventilation (more than 8 years of age and 25 kg in weight) were intubated with one of several techniques, including double-lumen endotracheal tube, selective left or right main-stem bronchus intubation with fiberoptic guidance, or standard endotracheal intubation. Routine monitoring included echocardiography, end-tidal carbon dioxide, transcutaneous oximetry, and blood pressure by automated cuff. Arterial lines were placed selectively. All patients were given general anesthesia. Those with cardiopulmonary dysfunction were anesthetized with a narcotic-relaxant technique (fentanyl/pancuronium), and those with minor lesions received inhalational anesthetic agents (halothane or isoflurane) and a muscle relaxant.

Basic surgical technique and instruments

PDA occlusion. Patients were placed in a right lateral decubitus position and four thoracostomies were made, each corresponding in size to the appropriate instrument for that position (from 2.7 mm for the grasper and videoscope to 7 mm for the large clip applier). The 2.7 mm diameter videoscope was used in all neonates weighing less than 2 kg ($n = 4$), and the 4 mm videoscope was used for those weighing more than 2 kg ($n = 27$). The left upper lobe was retracted inferomedially. Transient hypoxia and hypercarbia were corrected by repositioning the retractor

and reinflating atelectatic lung segments. The parietal pleura overlying the duct was elevated with the grasping forceps, and the cautery dissector was used to incise the pleura and develop a flap. The upper and lower duct angles were dissected without skeletonizing the duct, and the recurrent nerve was swept medially. When the upper and lower borders were free, the appropriately sized vascular clip was advanced through the posterior thoracostomy (not through a trocar) and placed around the duct, parallel to the aorta. Clip size was chosen to completely encircle the duct, to avoid impaling the wall. Preparations for volume infusion and thoracotomy were made before clip closure.

Real-time transesophageal echocardiography (TEE) was used to confirm complete interruption of ductal flow as the clips were applied. The aorta and left pulmonary artery were also examined by TEE before leaving the operating room in each case. Persistent ductal flow by TEE prompted placement of a second clip. If this was unsuccessful, a thoracotomy incision was made by connecting the two posterior thoracostomies, and the ductus was divided with an open technique. Single 12F thoracostomy tubes were positioned apically under direct vision.

Vascular ring division. Anesthesia, positioning, trocar placement, and exposure were as described for PDA interruption. Patients with respiratory symptoms underwent intraoperative bronchoscopy to localize the airway compression and rule out the presence of complete tracheal rings (which would mandate an open approach with cardiopulmonary bypass). With the subclavian artery used to orient dissection, the vascular ring elements were identified, freed from the underlying esophagus, and divided between vascular clips. Fibrous bands encircling the esophagus were lysed with the cautery probe. Pleural edges were cauterized to prevent lymphatic leak, and single 12F thoracostomy tubes were placed.

Additional procedures. The instruments and techniques developed for VATS PDA occlusion and vascular ring division were adapted to several other cardiovascular lesions.

Statistical methods. Data were reported as median and range and were analyzed by linear regression. By means of the exact binomial method, 70% confidence limits were given for proportions. An F test was used to compare variance between groups. Statistical significance was defined as $p < 0.05$.

Results

Animal experience. Between January and April 1993, VATS was performed in 19 animals whose ages ranged from 4 to 12 days (median 7 days) and weight from 1.35 to 3.48 kg (median 1.85 kg). Survivors, 16 of 19 (84%), were extubated within 1 hour of the operation and were able to walk and drink. Postmortem dissection, on the first postoperative day, demonstrated secure PDA occlusion (by probing the lumen) in each animal with no gross injury to the heart, lung, or chest wall. Improvement in technique and instrument design, as well as

Fig. 1. VATS PDA interruption and pericardial window. Results of animal experience showing the relationship between procedure number and procedure time (from incision to closure).

Table II. Results of VATS PDA interruption

	Elective operations	Premature infants
Patients	<i>n</i> = 25	<i>n</i> = 5
Procedures	<i>n</i> = 26	<i>n</i> = 5
Age	2.4 yr (47 days-14 yr)	18 days (16-31 days)
Weight	11.3 kg (3.6-46 kg)	1140 gm (575-2500 gm)
Highest ETCO ₂ in OR	42 (31-70)	33 (30-43)
Lowest O ₂ sat. in OR	99% (86%-100%)	98% (83%-100%)
Postop. stay	2 days (1-8 days)	38 days (24-60 days)
Complications	1*	1†
Mortality	0	0

Values are expressed as median and range. ETCO₂, End-tidal carbon dioxide; OR, operating room.

*Bleeding during open division necessitated transfusion.

†Transient left recurrent nerve paresis.

practice with the procedure, resulted in a significant reduction in procedure times ($p = 0.01$). The relationship between procedure time and procedure number is depicted in Fig. 1.

Complications. Three procedures were complicated and the animals were put to death immediately: a hemothorax developed during clip applicator insertion in one animal, lung trauma resulted from a retractor in another, and a pleural tent developed during trocar placement in the third, preventing videoscope insertion.

Clinical experience

PDA interruption. From April 1993 to March 1994, 30 patients with PDA underwent 31 VATS interruptions by one surgeon (R.P.B.). Results are summarized in Table II. There were 26 elective PDA closures and 5 urgent procedures in premature infants. In the elective PDA closure group, 6 of 25 (24%) had symptoms and 6 of 25 (24%) had other cardiac lesions, including bicommissural aortic valve ($n = 2$), small ventricular septal defects ($n = 3$), and mild left pulmonary artery stenosis ($n = 1$). The premature patients undergoing urgent PDA occlusion had a median gestational age of 27 weeks (range 24 to 36 weeks) and underwent VATS at a median age of 18 days (range 16 to 31 days). All were in congestive heart failure and ventilator dependent, and 3 had multiple organ system failure. All had had unsuccessful indomethacin therapy, and preoperative serum creatinine values ranged from 0.4 to 1.4 mg/dl (median 0.9 mg/dl).

The relationship between total operating room times, procedure times, and procedure number for all PDA procedures is depicted in Fig. 2. These times decreased by an average of 4.8 and 2.3 minutes per operation, respectively (significant at $p = 0.01$ and $p = 0.03$). There was a significant decrease in the variability of the operating room times ($p = 0.002$) from the first half of the experience to the last half, whereas there was no change in the variability

Fig. 2. VATS PDA interruption. Results of clinical experience showing the relationship between total operating room time (*solid line*), procedure time (*hatched line*), and procedure number.

of the procedure times. There was no significant difference in the operating room or procedure times between the premature patients and the patients having elective procedures. Seven PDA procedures (23%) had total operative times of more than 200 minutes, related to difficult exposure ($n = 3$), prolonged anesthesia time for single lung techniques ($n = 3$), and mechanical instrument failure (clip applier) necessitating thoracotomy ($n = 1$).

The incidence of residual ductal patency is presented in Table III. The premature infants were too small for the TEE probe and were assessed by intraoperative transthoracic echocardiography, which showed complete PDA interruption in all patients. Two patients had residual flow by intraoperative TEE after placement of a single clip, necessitating placement of a second clip. This was successful in one; however, the second patient, described later, had persistent flow and required open division. Follow-up echocardiography in the elective PDA group was obtained in 25 of 30 patients (83%), from 1 to 12 months after the operation (median 2 months). Three patients with no residual flow by intraoperative TEE subsequently had trace flow by Doppler interrogation at follow-up echocardiography, and one of these patients had a soft murmur.

Most patients having elective PDA interruption (81%) were extubated in the operating room. Four patients were extubated in the intensive care unit

Table III. Residual patency after VATS PDA interruption

Technique	Residual flow	Percent	70% CL (%)
Intraoperative	0/25	0	0-7.3
Discharge auscultation	1/30	3	0.5-10.8
Postop. echocardiography (median 2 mo)	3/25	12	5.4-22.6

from 2 to 4 hours after the operation. All chest tubes were removed on postoperative day 1. Eight of the last 10 patients were discharged the day after the operation. Follow-up reports from the referring physicians were obtained for all patients in the PDA group at a median of 1 month after the operation (range 1 week to 1 year) and confirmed complete wound healing in all patients, with no incisional pain.

COMPLICATIONS. No deaths occurred in the PDA group. Two patients underwent thoracotomy to complete the PDA procedure. In the first patient undergoing VATS PDA interruption, a 2.5 kg premature neonate (36 weeks' gestation) with a large ductus, the chest was opened intentionally after the duct dissection by VATS was completed, to minimize the risk of the first procedure (which was uncomplicated). The eighteenth elective operation, on a 9.4-month-old, 5.7 kg boy, was completed

Table IV. Results of VATS vascular ring division in eight patients

Anatomy	
Double aortic arch, atretic left arch, LLA	<i>n</i> = 3
Right aortic arch, aberrant LSCA, LLA	<i>n</i> = 5
Age	4.7 mo (42 days-5.5 yr)
Weight	6 kg (1.78-17.1 kg)
Total operating room time	245 min (155-275 min)
Postop. hospital stay	3 days (3-26 days)
Symptoms resolved	7/8 (88%)
Complications	1 (13.5%)
Mortality	0

Values are expressed as median and range. LLA, left ligamentum arteriosum; LSCA, left subclavian artery.

without difficulty, and intraoperative TEE showed complete ductal interruption. A murmur was heard 4 hours after the operation, however, and echocardiography confirmed a small residual PDA. Two days later, the patient underwent reoperative VATS placement of a second PDA clip. As the applier was closed, TEE demonstrated interruption of the residual ductal flow, but flow returned when the applier was released. Because of this mechanical failure, a thoracotomy was made, and the duct was divided. During open division, bleeding from the duct necessitated transfusion. The postoperative course was complicated by pleuropericardial effusions. The child was discharged on postoperative day 8 and was doing well at 3-month follow-up. The clip applier was thought to have failed as a result of mechanical stress and was replaced.

One premature patient had left-sided vocal cord paresis after the operation, documented by laryngoscopy. This child recovered and was discharged. There were no wound infections and no pneumothoraces necessitating tube thoracostomy.

Vascular ring division. Eight patients underwent VATS vascular ring division. All had symptoms before the operation, with airway obstruction alone (*n* = 2), esophageal obstruction alone (*n* = 3), or both (*n* = 3). Two patients were born prematurely at 27 and 33 weeks of gestation; the former infant required an urgent operation at 42 days after birth for increasing airway pressures on mechanical ventilation. Three patients had concomitant medical problems, including ventricular septal defect (*n* = 1), laryngomalacia (*n* = 1), and chronic renal failure (*n* = 1). Preoperative studies included barium swallow and echocardiography in all patients. Five patients had preoperative magnetic resonance imaging.

Operative results are summarized in Table IV. Follow-up interviews and examinations from 1.5 to 9.5 months (median 5.9 months) after the operation demonstrated complete wound healing in all patients with symptomatic improvement in seven of eight (88%). After VATS vascular ring division, the premature infant with increasing airway pressures had immediate improvement in respiratory function and was extubated 3 days later. One patient with preoperative stridor and regurgitation had persistent but less severe stridor after division of a left-sided ligamentum arising from an aberrant left subclavian artery and a right aortic arch. Follow-up magnetic resonance imaging and bronchoscopy revealed mild right lateral tracheal compression above the carina.

COMPLICATIONS. No operative deaths occurred in the vascular ring group. Three patients required limited thoracotomies, connecting the posterior two thoracostomies, to divide patent vascular structures discovered during the thoroscopic dissection (*n* = 2) and to control bleeding (*n* = 1). The latter patient had a right aortic arch with an aberrant left subclavian artery. When the ligamentum was divided (between vascular clips), bleeding obscured the operative field. Immediate thoracotomy was performed, and the hemorrhage was localized to a small adventitial vessel and controlled. No transfusion was required and the patient recovered.

One patient had chylothorax after division of a left ligamentum arising from an aberrant left subclavian artery, which required a second VATS procedure to ligate the leaking lymphatic vessel. The subsequent recovery was uneventful.

Additional procedures. Nine VATS procedures were performed for diverse cardiovascular lesions (Table V). VATS was used in several patients with complex congenital heart disease. A 12-year-old patient with a single ventricle, who previously had a palliative Fontan procedure, presented with increasing cyanosis. He had an arterial oxygen saturation of 86% in room air, resulting from a large venous collateral diverting blood from the innominate vein to the left atrium. Attempts at transcatheter occlusion were unsuccessful and he was referred for VATS collateral interruption, which was performed through the left side of the chest. Within minutes of collateral ligation, the patient's arterial oxygen tension increased from 82 to 323 mm Hg (inspired oxygen fraction 100%). He was extubated in the operating room and discharged the next morning. At 5-month follow-up, the patient had no incisional pain, and the transcutaneous oxygen saturation was 98%.

Table V. VATS additional procedures

Patient	Age	Weight	Diagnosis	Procedure	Required thoracotomy	Complication	Stay	Outcome
1	4 days	3.1 kg	TOF/PS, AP collaterals	Collateral interruption (arterial)	Yes	None	31 days	Discharged, doing well
2	12 yr	32 kg	Cyanotic after Fontan operation	Collateral interruption (venous)	No	None	2 days	Discharged, doing well
3	6 yr	18 kg	Recurrent pneumonia	Diagnostic VATS	No	None	3 days	Negative exploration, discharged, doing well
4	2 hr	1.4 kg	Congenital heart block, fetal hydrops	Epicardial pacemaker	Yes	None	93 days	Grew to 2 kg, permanent pacer placed, discharged, doing well
5	36 days	1.8 kg	Pericardial effusion after repair of aortic arch and VSD	Pericardial drainage	No	MSOF	37 days	Died in hospital
6	17 days	3.2 kg	Pericardial effusion after atrial septectomy/shunt	Pericardial drainage	No	None	5 days	Discharged, no effusion by echo, to return for BDCPA/Fontan, doing well
7	12 yr	54 kg	Pericarditis, JRA	Pericardial resection	Yes	None	10 days	Discharged, no effusion by echo, doing well
8	3.3 yr	16 kg	Pericardial effusion after TOF repair	Thoracic duct interruption	No	Persistent effusion required thoracotomy and duct ligation	25 days	Discharged, clear CXR, doing well
9	6 yr	17 kg	Chylothorax after VATS vascular ring division	Lymphatic ligation	Yes	None	2 days	Discharged, clear CXR, doing well

AP, Aortopulmonary; BDCPA, bidirectional cavopulmonary anastomosis; CXR, chest x-ray; stay, postoperative hospital stay; MSOF, multisystem organ failure; TOF/PS, tetralogy of Fallot/pulmonary stenosis; VATS, video-assisted thoracoscopic surgery; VSD, ventricular septal defect; JRA, Juvenile rheumatoid arthritis.

Four patients in this group required thoracotomy to complete their procedures. In two patients this was done for safety: improving vascular control during division of an aortopulmonary collateral in a 3.1 kg patient with tetralogy of Fallot and pulmonary atresia and facilitating hemostasis during pericardial resection in a patient with unanticipated dense, vascularized pericardial adhesions. In two patients instrument limitations led to thoracotomy. A 2-hour-old premature neonate weighing 1.4 kg, with fetal hydrops as a result of congenital heart block, required a small thoracotomy to complete placement of an epicardial pacemaker lead that was too large to be safely manipulated in the pleural space. The patient subsequently recovered well and

was eventually discharged. In the second case, a prototype VATS needle holder was inadequate for suturing the parietal pleura in a 17.1 kg patient with persistent chylothorax 9 days after VATS vascular ring division. A 3 cm left lateral thoracotomy admitted a standard needle holder, and the chylous leak was effectively controlled. One additional patient required a thoracotomy for persistent chylothorax after VATS thoracic duct ligation. The patient was a 3-year-old child in whom a right chylothorax had developed after complete repair of tetralogy of Fallot. A VATS thoracic duct ligation was performed through the right side of the chest. No intraoperative problems developed, and the thoracic duct and surrounding tissues were ligated at the

Table VI. *Clinical VATS results*

<i>Procedure</i>	<i>n</i>	<i>Technical success*</i>
PDA		
Elective	25/26	96%
Premature	4/5	80%
Vascular ring	5/8	63%
Other procedures	5/9	56%
Total	39/48	81%

*Procedure was completed without thoracotomy.

aortic hiatus with vascular clips and intracorporeal suture ligation. The chylous drainage persisted after the operation, and after 7 more days the patient underwent open ligation. At thoracotomy, the VATS ligation looked secure, and no leak was identified. Mass ligation was performed beneath the previous VATS ligation, the drainage ceased, and the patient recovered.

COMPLICATIONS. One premature neonate died of multiple organ system failure, 39 days after a VATS pericardial window, unrelated to the procedure. Follow-up interviews were obtained in eight of the nine surviving patients from 10 days to 8 months (median 4 months) after the operation. These revealed symptomatic improvement in all, with no wound infections or chest wall pain.

Discussion

We have shown that VATS can be safely applied to neonates, infants, and children with diverse congenital cardiovascular lesions. The justification for pursuing the VATS approach—to minimize surgical trauma—must be compelling, given the known efficacy of open techniques. The potential long-term morbidity of thoracotomy includes scoliosis, breast deformity, winged scapula, shoulder weakness, reduced shoulder mobility, and chest wall pain syndromes.⁴⁻⁷ A pure VATS technique might reduce these sequelae because chest wall muscles are not cut, ribs are not retracted, intercostal ligaments are not stretched, and incisions are smaller. Short-term follow-up observations in adult patients suggest that VATS decreases early postoperative chest wall pain, producing less respiratory dysfunction and shorter hospital stays.⁸ Chest wall pain is difficult to quantify in neonates and infants; however, we have observed rapid return to full activity after VATS procedures, leading to short hospitalizations.

Laboratory experience was essential to develop safe instruments and techniques, in the absence of

prior experience with VATS cardiovascular procedures in newborn infants. Size constraints altered anesthetic approaches and surgical techniques. Instruments from other surgical specialties, including orthopedics and otolaryngology, were adapted to pediatric cardiothoracic VATS, and several new instruments were designed. The total operating room times for PDA interruption showed more variability in the first half of the experience, as the operative team became familiar with the technique, whereas procedure times (which more accurately reflected the surgeon's practice in the animal laboratory) did not vary significantly over the course of the clinical experience, while decreasing steadily. Experience and improved instruments should decrease the likelihood of unplanned conversion to thoracotomy, which was 3% for PDA interruption (excluding the planned thoracotomy in the first patient) and 44% in the additional procedures, in which instruments and techniques were not as well developed (Table VI). Conversion to a thoracotomy negates much of the advantage of the thoracoscopic approach and should be considered a technical failure, stimulating efforts to improve technique or instruments.

Ironically, PDA, a relatively simple lesion, now presents a clinical conundrum, with multiple therapeutic options and no clearly superior approach. Concerns about the long-term functional and cosmetic effects of thoracotomy are driving the pursuit of less traumatic approaches. Minimally invasive transcatheter techniques are limited by various exclusion criteria, based on patient size (5.2F introducer sheaths for devices will not fit the femoral vessels of infants weighing less than 4 kg) and ductal anatomy (coils are not secure in short PDAs or those over 2.5 mm in diameter⁹), which may not be apparent until catheterization. The risks of device embolization¹⁰ and catheterization¹¹ must also be considered, as well as the theoretical risk of arteritis in patients with an intravascular foreign body. PDA interruption can be effectively performed with VATS,² with minimal chest wall trauma and rapid recovery, without restrictions based on patient size or duct anatomy. Experience with VATS PDA interruption is too preliminary to determine the risk of hemorrhage, recurrent nerve injury, chylothorax, and pulmonary artery distortion. Assessed by Doppler echocardiography, the most sensitive and reproducible standard available, our short-term incidence of residual PDA flow (12% at 2 months) compares favorably with results with the Rashkind transcath-

eter device (38% at 1 year¹²) and open surgical ligation (23% at 4 months¹³). VATS may combine the reduced trauma of the transcatheter techniques with the efficacy of open surgical ligation, without introducing complex exclusion criteria. An effective VATS procedure should also be included in the therapeutic strategy for PDA in premature newborn infants, in whom indomethacin therapy, with residual patency as high as 21%,¹⁴ holds primacy in the absence of a less invasive approach. Given the recent controversy regarding the relative cost and efficacy of transcatheter devices and open surgical techniques¹⁵ and the introduction of VATS, a prospective trial would be useful to clarify the appropriate treatment algorithms for PDA.

VATS vascular ring division can be accomplished in patients with the appropriate anatomic substrate. Right aortic arch with aberrant left subclavian artery and left ligamentum, and double aortic arch with an atretic left arch constitute a majority of vascular rings in most series.¹⁶ These rings, and most of the rarer forms, can be divided by VATS, with the use of techniques similar to those for PDA interruption. Until effective endoscopic vascular clamps are available, caution dictates that patent vascular structures necessitating division should be approached with at least a limited thoracotomy.

Finally, VATS should be considered in the management of complex congenital heart defects. A minimally invasive approach may be advantageous in patients undergoing staged repair of cyanotic heart defects, certainly by decreasing chest wall trauma and possibly by limiting collateral formation. Reduced chest wall scarring may also attenuate the risks of reoperation in patients requiring multiple staged procedures. With further development, VATS could be applied to diaphragm plication, lung and heart-lung transplant biopsies, pulmonary artery banding, and interruption of anomalous left superior vena cava. Further technique and instrument development should address several problems including prolonged VATS procedure times, limited vascular control, and the frequent need to convert to thoracotomy. Efforts must also be made to document prospectively that the goals of pediatric VATS—reduced pulmonary dysfunction, chest wall trauma, pain, hospital stay, and cost—are being achieved without compromising surgical results.

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Discussion

Dr. Antonio F. Corno (*Milan, Italy*). I have a couple of questions. First, did you compare the patency rate you observed after PDA closure with this technique with the other conventional surgical technique or with the interventional cardiology approach? Second, did you ever use this technique to treat patients with paralysis of the diaphragm because of phrenic nerve damage? If not, can you use your animal model to study this application?

Dr. Carl Lewis Backer (*Chicago, Ill.*). This innovative use of VATS techniques may have some promise for selected pediatric patients. For comparison, I thought I would share with you our experience with open thoracotomy for the diagnosis of PDA. We recently reviewed our results at Children's Memorial Hospital with division and oversewing of a PDA and presented this to the American Surgical Association. Between 1947 and 1993, 1088 children underwent division and oversewing of a PDA through an open thoracotomy. In that group of more than 1000 patients there was no mortality or significant morbidity. In the follow-up, for which color Doppler echocardiography and, in some circumstances, cardiac catheterization for other indications were used, there were no recurrences. Twenty patients during the same time period had simple ligation, and there was one recurrence in this group in a child on whom Dr. Potts operated very early in the series. We would maintain that this gold standard of no mortality and no recurrence in more than 1000 patients having open thoracotomy and oversewing and division compares favorably with your 12% recurrence rate. We have used a muscle-sparing thoracotomy, limited use of chest tubes, and same day admission surgery, so that the mean hospital stay is now only 3.8 days. This length of stay comes very close to the results with the VATS procedure.

I have two questions. The first relates to the patient with a vascular ring. When a vascular ring is divided, the tension on that vessel causes the two stumps to retract. Even after oversewing the stumps I am sometimes a little nervous, because the stump can retract into the posterior mediastinum once the clamp is removed. I wonder if these patients with a vascular ring are at increased risk of life-threatening hemorrhage with the VATS technique.

Second, have you evaluated the cost of the VATS approach? In the study of the percutaneous transcatheter ductus device, there was no question that the device was more expensive than an open thoracotomy. With the cost of having two assistants, having a longer operating room time, and having to use more complex disposable equipment, I wonder whether the cost is actually going to be more than in a standard open thoracotomy even though the patient may be going home 1 day earlier.

Dr. William G. Williams (*Toronto, Ontario, Canada*). We have had one disaster from a PDA clip eroding into the bronchus. That may not mean that we should not use clips, but it does mean that we should be careful how they are positioned. Do you have enough flexibility through a scope to position the clip so that it is not protruding toward the esophagus or airway?

If a 6-month-old child with a PDA were admitted to your facility, would he or she be sent to the catheterization laboratory or to the operating room to have the PDA occluded.

At what point do you consider a ductus too large to close by your technique?

Dr. Burke. Perhaps the most sensitive test available to assess PDA procedures is Doppler interrogation for residual flow. According to that standard, the incidence of residual flow after Rashkind device placement is 38% at 1 year, 23% after open surgical ligation, and 12% in our VATS experience.

We have considered the use of VATS for diaphragm plication, especially in neonates with phrenic nerve injury after cardiac operations who cannot be weaned from the ventilator. We have devised a technique of suturing the dome of the diaphragm, bringing the suture out the anterior chest wall.

Dr. Backer's group has achieved excellent results after PDA division. As our instruments have evolved, our incidence of trace residual Doppler flow has decreased, but without dividing the ductus, we will have some incidence of residual flow. Our cardiologists consider an audible murmur evidence of significant residual flow, but we do not know the clinical importance of trace Doppler flow.

The motivation to pursue the VATS technique is the same force driving the cardiologists to devise transcatheter techniques. We more closely approximate sound surgical principles with VATS than is possible during catheterization. Small incisions for PDA operations do not compare with VATS. Attempting PDA division through very small incisions compromises visualization and maneuverability. VATS instruments readily illuminate and magnify small spaces and are designed to be manipulated in confined areas.

Endoscopic clamps are being developed for VATS vascular ring division. We currently exclude patients who require division of patent vascular structures.

Until mechanical arms are developed to handle instruments, we need two assistants. Ten of our last 12 PDA patients were discharged the day after the operation, so we anticipate decreased costs.

Clip appliers and lung retractors were difficult to design. We use an angled clip applier, with three clip sizes. Ideally, we will develop effective intracorporeal suturing techniques.

Our cardiologists support the VATS approach, perceiving that the patients have less chest wall pain after the operation and a low incidence of residual flow. Most patients presenting to Children's Hospital with PDA are referred for VATS interruption.

Our largest clip has a diameter of 11 mm. We will not attempt VATS on a ductus larger than 1 cm to avoid the risk of impaling the duct.