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When to consider a posterolateral descending aortopexy in addition to a posterior tracheopexy for the surgical treatment of symptomatic tracheobronchomalacia ☆

Wendy Jo Svetanoff [a,1], Benjamin Zendejas [a,1], Leah Frain [b], Gary Visner [b], Charles J. Smithers [a], Christopher W. Baird [c], Sanjay P. Prabhu [d], Russell W. Jennings [a,2], Thomas E. Hamilton [a,⁎,2]

[a] Department of Surgery, Boston Children's Hospital, Boston, MA
[b] Division of Pulmonary Medicine, Boston Children's Hospital, Boston, MA
[c] Department of Cardiac Surgery, Boston Children's Hospital, Boston, MA
[d] Department of Radiology, Boston Children's Hospital, Boston, MA

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ABSTRACT

Purposes: The descending thoracic aorta typically crosses posterior to the left mainstem bronchus (LMSB). We sought to evaluate patient factors that may lead one to consider a posterolateral descending thoracic aortopexy (PLDA) in addition to a posterior tracheopexy (PT) in the surgical treatment of symptomatic tracheobronchomalacia (TBM) that involves the LMSB.
Methods: Retrospective review of patients who underwent PT with or without PLDA between 2012 and 2017. Severity and extent of TBM were assessed using dynamic tracheobronchoscopy. Aortic positioning compared to the anterior border of the spine (ABS) at the level of the left mainstem bronchus was identified on computed tomography (CT). Factors associated with performing a PLDA were evaluated with logistic regression.
Results: Of 188 patients who underwent a PT, 70 (37%) also had a PLDA performed. On multivariate analysis, >50% LMSB compression on bronchoscopy (OR 8.06, $p < 0.001$), >50% of the aortic diameter anterior to the ABS (OR 2.06, $p = 0.05$), and more recent year of surgery (OR 1.61, $p = 0.003$) were associated with performing a PLDA.
Conclusion: When performing a PT, a PLDA should be considered for patients who have >50% LMSB compression on dynamic bronchoscopy, and in those with a descending thoracic aorta located >50% anterior to the ABS.
Level of evidence: III
Type of study: Retrospective comparative study.

Tracheobronchomalacia (TBM) is the most common congenital tracheobronchial abnormality, with an incidence of approximately 1 in 2100 children [1]. The diagnosis of TBM can be elusive, and even when diagnosed, there is no consensus on management of the disease [2]. TBM is best identified by three phase dynamic tracheobronchoscopy, as standard tracheoscopy or even rigid bronchoscopy alone can underestimate the severity of tracheobronchomalacia [3]. TBM is caused by excessive collapse of the airway during exhalation. Patients can present with persistent cough, dyspnea on exertion, recurrent infections, brief resolved unexplained events (BRUEs), or difficulty weaning from mechanical ventilation [1,3–8]. Primary TBM is thought to be congenital in nature, often associated with a history of esophageal atresia (EA) or prematurity and is associated with a widening of the posterior tracheal membrane, while secondary TBM is felt to be caused by extrinsic vascular compression [3–6,10,11]. Anterior tracheal compression, which is often a fixed tracheal stenosis, can often be relieved by suturing the great vessels (anterior aortopexy) and/or the trachea (anterior tracheopexy) to the sternum [7,12]. On the contrary, posterior tracheal membranous intrusion is a usually dynamic process which is most evident with forced exhalation, and in some cases, is the main contributor for the collapse of the airway [13].

Since 2012, our institution has pioneered an innovative surgical approach to treat posterior membranous intrusion by directly suturing the posterior tracheal membrane to the anterior spinal ligament, effectively creating a posterior tracheopexy (PT) [1]. Through either a thoracotomy (often right-sided with a left aortic arch) or via thoracoscopy (with or without robotic assistance), the membranous portion of the posterior

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⁎ Corresponding author at: Boston Children's Hospital 300 Longwood Ave, Fegan 3, Boston, MA 02115. Tel.: +1 617 355 7800; fax: +1 617 730 0477.
E-mail address: thomas.hamilton@childrens.harvard.edu (T.E. Hamilton).
[1] Co-First Authors.
[2] Co-Senior Authors.

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trachea, as well as the mainstem bronchi (posterior bronchopexy) if malacic, is sutured to the anterior longitudinal spinal ligament under flexible bronchoscopic guidance to improve airway patency and prevent posterior membrane intrusion [1,8,9,14,15].

Recently, we have recognized that the respective location of the descending thoracic aorta with regards to the spine and its impact on the mainstem bronchi are variable, and understanding these relationships becomes critical for the surgical management of TBM. In some patients, varying degrees of the total circumference of the descending aorta can be situated anteriorly compared to the anterior border of the spine, causing extrinsic posterior compression of the left mainstem bronchus (Fig. 1A–D) [14]. Furthermore, performance of a posterior tracheopexy without addressing the anteriorly placed descending aorta can exacerbate the extrinsic vascular compression of the left mainstem bronchus (LMSB). In these cases, a posterolateral descending aortopexy (PLDA) is performed by mobilizing the aorta proximal and distal to the LMSB, placing sutures to displace it posteriorly from the LMSB and towards the left side of the spine. This provides the needed space in order to support the posterior membrane of the LMSB onto the spine to treat the LMSB malacia [14]. Both the percentage of the aortic diameter that is located in front of the spine (as seen on contrast-enhanced chest computed tomography [CT] scan) and the amount of LMSB compression (visualized during a dynamic tracheobronchoscopy) can be assessed during the preoperative planning phase to determine the likelihood that a descending aortopexy will be needed; the diagnostic thresholds to assist with the decision to proceed with such an approach are the subject of this investigation.

When considering moving the descending aorta, the position of the artery of Adamkiewicz (AoA) needs to be taken into consideration. Also known as the great radicular artery, the AoA arises from the descending aorta and is the main artery supplying the central anterior spinal cord. This artery usually originates from the left side of the aorta, most frequently between the T9 and T11 levels, to supply blood to the anterior spinal artery [16]. However, wide variations in the origin of the artery can exist [16]. Blood supply to the spinal cord can be compromised during surgical procedures involving displacing the descending thoracic aorta and may lead to devastating neurological complications, most notably, paraplegia [16]. Hence, identification of the AoA is crucial during surgery for TBM when a descending aortopexy is planned to avoid injury to this major arterial supply to the anterior spinal cord and prevent development of serious neurological sequelae.

With this work, we aimed to identify which demographic, imaging, or preoperative bronchoscopic variables may predict which patients

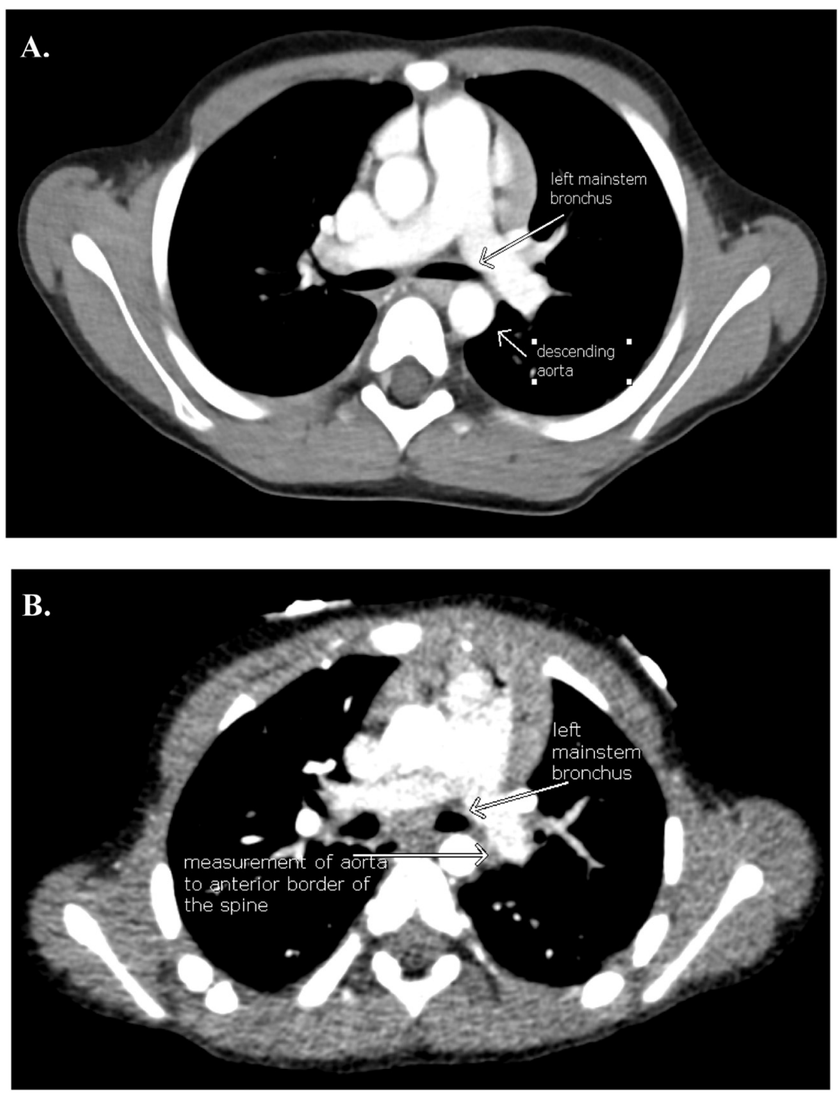

Fig. 1. (**A–D**) CT images representing the four categories used to describe the location of the descending aorta compared to the anterior border of the spine (ABS). Measurements were performed at the level where the left mainstem bronchus crosses anterior to the aorta. (**A**) Less than 25% of the descending aortic diameter is located anterior to the ABS. (**B**) 50% of the aortic diameter is located anterior to the ABS. (**C**) Between 50% and 75% of aorta is located anterior to the ABS. (**D**) The entire aorta is anterior to the spinal column. This patient also has a right aortic arch.

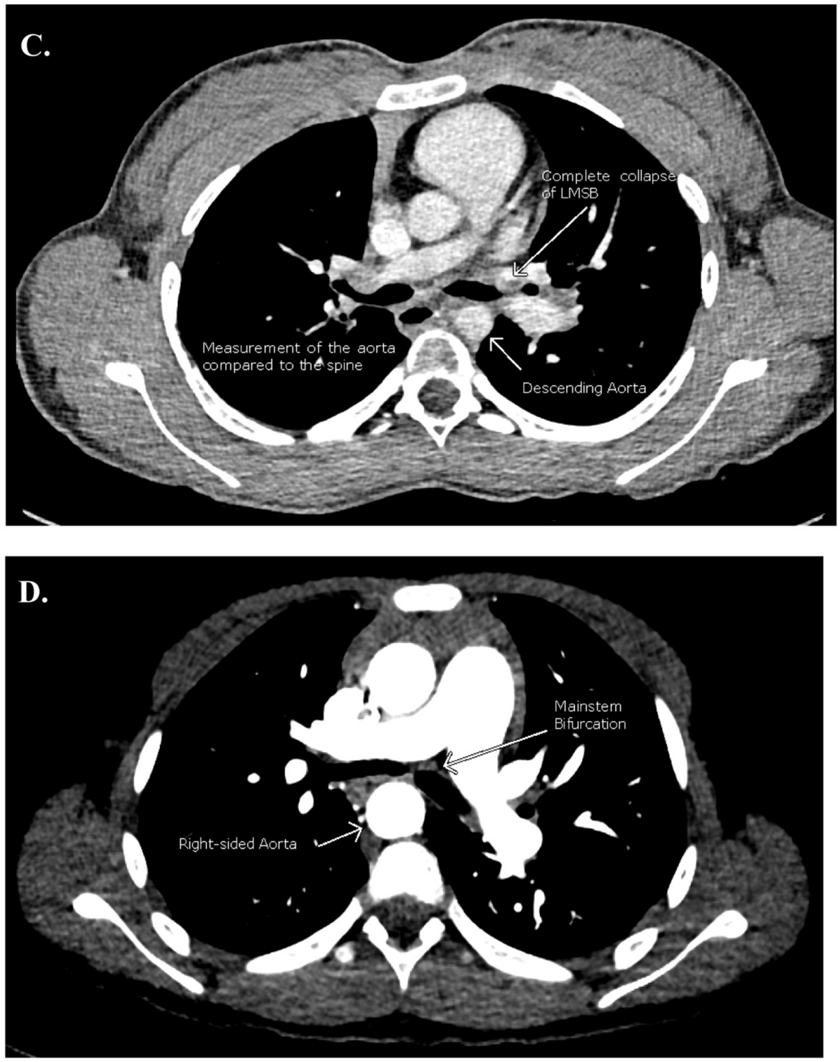

Fig. 1. (*continued.*)

may benefit from a descending aortopexy at the time of their posterior tracheopexy in order to address a malacic LMSB. Being able to predict which patients may need a posterolateral descending aortopexy may allow us to better counsel patients and optimize our surgical planning. Similarly, we sought to determine the frequency in which the AoA would be at risk in our operative field and to quantify the added morbidity of a posterolateral descending aortopexy.

1. Methods

With IRB approval, a retrospective chart review was performed of all patients who underwent a posterior tracheopexy for symptomatic TBM from May 2012 to October 2017. Demographics, including gender, age at surgery, history of prematurity, EA, tracheostomy, presence of associated great vessel anomalies [17], and concurrent esophageal or cardiac procedures performed at the time of posterior tracheopexy were recorded.

1.1. Preoperative evaluation

Patients with symptoms concerning for tracheomalacia undergo a diagnostic rigid dynamic 3-phase bronchoscopy (spontaneous ventilation, forceful cough, and distention) to evaluate the location and extent of tracheobronchomalacia and to identify any associated pathologies such as tracheoesophageal fistula, tracheal diverticulum or aberrant bronchial anatomy. As previously described, we follow a specific classification scheme to describe the location and grade the severity of TBM as determined by the percent of airway collapse during the different phases of the dynamic bronchoscopy [9]. The amount of LMSB compression, also categorized as less than 25%, 25%–50%, 50%–75%, or 75%–100%, was determined from this dynamic bronchoscopy.

Patients with symptoms and bronchoscopic evidence of TBM who are anticipating surgical repair then undergo a contrast enhanced CT scan of the chest. The degree of anterior displacement of the descending thoracic aorta is evaluated by examining the axial images of the contrast enhanced chest CT scan. The distance between the anterior border of the spine (ABS) and the anterior border of the descending aorta is measured at the level where the left mainstem bronchus crosses anteriorly to the descending thoracic aorta (Fig. 2). The percentage of the aortic diameter that is located anterior to the ABS is calculated and categorized as less than 25%, 25% to 50%, 50% to 75%, or greater than 75%.

Beginning in 2016, we implemented a process for the identification and report of the location of the artery of Adamkiewicz (AoA) in our radiologic evaluation of the chest CT scans that our patients with symptomatic TBM undergo as part of their preoperative workup. The level of the AoA is determined by its relationship to the vertebral bodies. The intervertebral foramen at which the spinal branch of the segmental artery enters the spinal canal and continues as the artery of Adamkiewicz is interpreted as the AoA level (Fig. 3). For example, if the spinal branch entered between the 12th thoracic (T) vertebra and

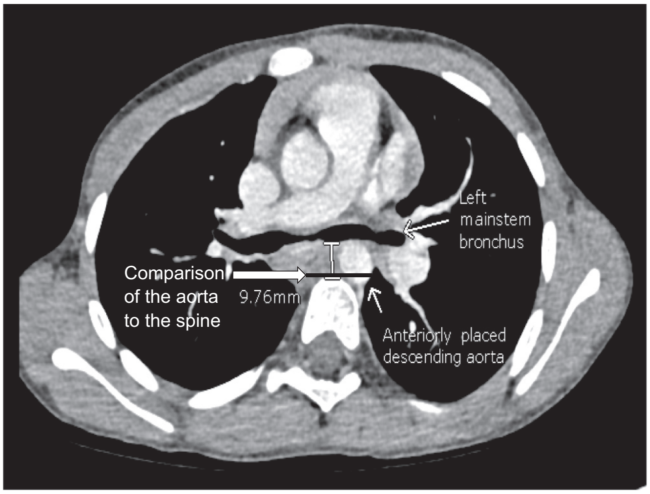

Fig. 2. Example of the measurement between the anterior spinal border (ABS) and the aortic diameter as seen on preoperative imaging. All measurements were done at the level where the mainstem bronchus crossed over the descending aorta. This patient had an aorta that was 75%–100% anterior to the spin, and a left mainstem bronchus that was 75% collapsed on bronchoscopy.

the first lumbar (L1) vertebra, the localization is denoted as segmental level T12.

1.2. Surgical technique

We have previously described our technique for posterior tracheopexy [8,9]. The decision to perform a thoracic posterolateral descending aortopexy (PLDA) was based on the combination of the degree and extent of LMSB malacia seen on preoperative bronchoscopy and on the location of the aorta with respect to the spine; however, no particular thresholds were actively followed during the time-frame under study. When performing a posterolateral descending aortopexy, sufficient length for posterior aortic displacement is obtained by mobilizing the aorta and intercostal branches one to two centimeters proximally and distally at the level where it crosses posteriorly to the left mainstem bronchus. Great care is taken to identify and protect the thoracic duct. Division of intercostal branches is only performed when required in order to provide enough mobility of the aorta for exposure of the anterior spinal ligament at the appropriate level for the PLDA, for which knowledge of the location of the AoA is imperative. Fine permanent monofilament sutures with small autologous tissue pledgets (azygous vein, pleura, or muscular fascia) are placed on the adventitia of the anterior wall of the descending aorta in a horizontal mattress configuration and anchored to the desired side of the spine (often left side, but can be right side if a right aortic arch with a right-sided descending aorta is present) to effectively roll and posteriorly displace the descending thoracic aorta adjacent to the spine, with the goal of creating space for the posterior bronchopexy by displacing the aorta posterolaterally (Fig. 4). Two to three stitches are typically required, making sure to place one above and one below the location where the LMSB crosses. On occasion, the aortic arch also needs to be moved in a cephalad and posterior direction to offload its pressure on the left mainstem bronchus. Care should to be taken to ensure that the depth of each stitch is limited to the outer wall of the aorta; if the stitch were to be too deep, as evidenced by oozing around the suture line or needle, one must remove this stitch, hold pressure, and try again in a slightly different spot at a more shallow depth to avoid a full thickness bite which risks catastrophic bleeding. Similar to our PT technique, real-time flexible intraoperative bronchoscopy is crucial to precisely place the bronchopexy stitches, monitor their effects on airway patency and avoid tracheal and/or bronchial deformity. In addition, for cases where we perform a PLDA, we place upper and lower extremity arterial lines to monitor blood pressure and ensure that there is no change in lower extremity perfusion pressure after the PLDA. [9] Given the excellent exposure to the posterior membranous trachea from a posterior right thoracotomy, most of our posterolateral descending aortopexies are performed via this approach, though in select cases of isolated left mainstem malacia, or in situations where a left thoracotomy is more convenient for other reasons, a PLDA can be performed via the left chest as well. Notably, when performing a PLDA via the right chest, one must do the PLDA prior to the PT in order to maintain adequate exposure. It is unclear the length of time the addition of a posterolateral descending aortopexy adds to the operation and is a variable we aim to study.

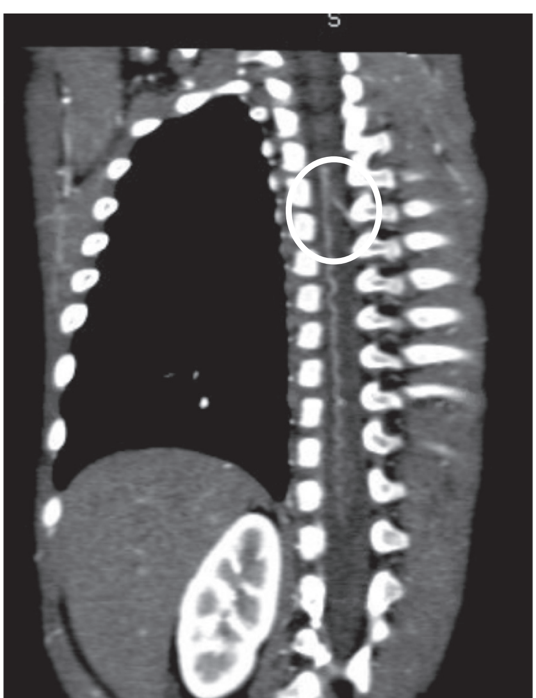

Fig. 3. CT evaluation of the position of the artery of Adamkiewicz. In this coronal plane, the artery of Adamkiewicz connects with the anterior spinal artery between the T5 and T6 thoracic vertebrae.

1.3. Statistical analysis

For analysis purposes, patients were divided into two groups: those who underwent a PLDA in addition to a PT during their surgical correction of TBM and those that underwent a PT only. Univariate analysis was performed for demographic and preoperative diagnostic variables. Gender, history of EA, history of tracheostomy, presence of great vessel anomaly and concurrent esophageal or cardiac procedures at the time of PT were treated as binary variables. Gestational age was first collapsed into premature (<37 weeks' gestation) and full-term; further analysis dichotomized gestational age into extreme prematurity (<30 weeks' gestation) or not. Age at surgery was treated as a continuous variable. LMSB malacia was categorized into four groups for analysis based on their degree of collapse on active cough phase of the bronchoscopy: 0%–25%, 25%–50%, 50%–75%, and 75%–100%. The percent of aortic diameter that was anterior to the border of the spine (ABS) was similarly categorized into 0%–25%, 25%–50%, 50%–75%, and 75%–100%. Predictors of needing a PLDA were evaluated first with univariate associations using the Chi-Square or Wilcoxon Rank Sum test; variables with a p-value <0.20 were further evaluated with logistic regression in multivariate modeling. Statistical significance was determined with a p-value of 0.05. SAS® 9.4 (SAS Institute Cary, NC) was used for statistical analysis.

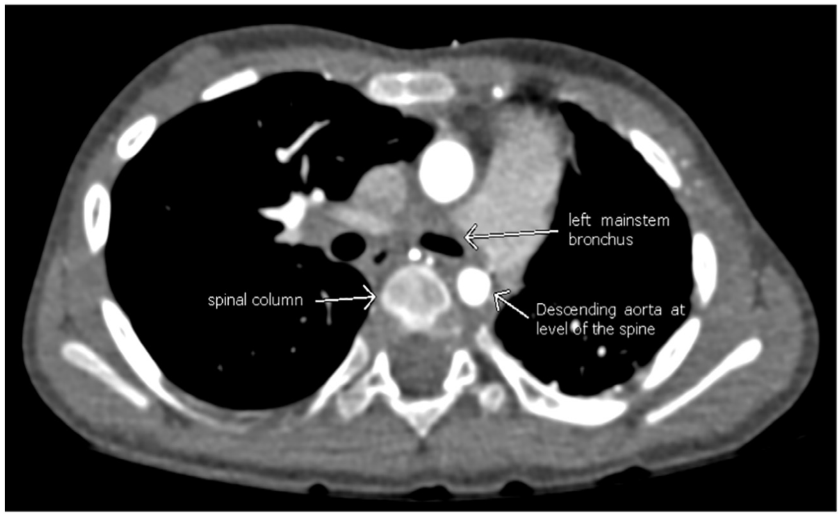

Fig. 4. Postoperative imaging of the chest showing the posterior and lateral displacement of the descending aorta after the performance of a posterolateral descending aortopexy. The entire diameter of the aorta is parallel or even slightly posterior to the anterior border of the spine that is adjacent to the aorta.

Table 1
Demographic univariate analysis of patients with tracheobronchomalacia between those who underwent a descending aortopexy and those that did not (PT = posterior tracheopexy, PLDA = posterolateral descending aortopexy, EA = esophageal atresia).

Demographics	Total number = 188	PT with PLDA = 70	PT alone = 118	Odds ratio	95% CI	P-value
Male gender	111 (59%)	40 (57%)	71 (60%)	0.88	0.48–1.61	0.68
Premature (≤36 weeks)	91 (48%)	32 (43%)	59 (50%)	0.82	0.47–1.52	0.57
Extreme prematurity (≤30 weeks)	17 (9%)	6 (9%)	11 (9%)	0.91	0.32–2.59	0.86
History of EA	134 (71%)	41 (59%)	93 (79%)	0.38	0.20–0.73	<**0.01**
Preop trach	22 (12%)	7 (10%)	15 (13%)	0.76	0.30–1.97	0.58
Great vessel anomaly	106 (56%)	21 (30%)	16 (14%0	2.73	1.31–5.70	<**0.01**
Age at surgery	3.1 years	3.6 years (66 days–19.5 years)	2.8 years (1 day–22.4 years)	1.00	1.0–1.0	0.23
Year of surgery[a]	–	–	–	0.312	0.08–0.55	<**0.01**
Concurrent esophageal procedures	67 (36%)	19 (27%)	48 (41%)	0.54	0.29–1.03	*0.06*
Concurrent cardiac procedures	7 (4%)	1 (1%)	6 (5%)	0.27	0.03–2.3	0.23

[a] Being a count variable, analysis using the variable year of surgery was performed using Poisson regression.

2. Results

Between May 2012 and October 2017, a total of 209 patients were identified as undergoing surgery for symptomatic TBM. Twenty-one of these patients had only anterior airway work (anterior aortopexy/tracheopexy) via sternotomy and were excluded from the study; 188 patients had a posterior tracheobronchopexy and were the target group for our study. The posterior tracheobronchopexy group was classified into those with a PT who received the addition of a PLDA ($n = 70$) and those who did not ($n = 118$).

2.1. Univariate analysis

On univariate analysis, gender, history of prematurity, extreme prematurity, age at surgery and the performance of concurrent cardiac procedures were similar between the two groups (Table 1). The PLDA group was more likely to have an associated great vessel anomaly (OR 2.73, CI = 1.31–5.70, p = <0.01). The PLDA group was significantly less likely to have a history of esophageal atresia (OR = 0.38, CI = 0.20–0.73, p < 0.01) and we encountered a nonsignificant trend towards not performing a concurrent esophageal surgery (i.e. Foker I, stricture resection, or jejunal interposition) at the same time as the PT with the PLDA group. (OR 0.54, 95% CI 0.29–1.03, p = 0.06) (Table 1).

Patients with less than 25% of the diameter of the descending aorta located anterior to the ABS were less likely to have undergone a PLDA at the time of surgery (OR = 0.34, 95% CI = 0.14–0.83, p = 0.02), while patients with 50%–75% of the descending aorta located anterior to the spine had a nonsignificant trend towards undergoing a PLDA along with PT (OR 1.92, 95% CI 0.92–4.0, p = 0.08). All other locations of the aorta were not found to significantly associate with the performance of a posterolateral descending aortopexy on univariate analysis (Table 2).

On preoperative bronchoscopy, there was a significant association between the amount of LMSB compression and whether the patient received a PLDA at almost all levels of compression (Table 3). Patients who had <25% LMSB compression were significantly less likely to have received a PLDA (OR = 0.21, 95% CI = 0.10–0.45, p < 0.01). On the converse, patients who had >50% LMSB compression were significantly

Table 2
The percentage of aortic diameter that was anteriorly placed relative to the anterior border of the spine (ABS) was compared between patients who received a posterolateral descending aortopexy (PLDA) and those that did not. A larger percentage of patients who did not receive a PLDA had <25% of the aorta situated anterior to the ABS (PT = posterior tracheopexy).

Percent of aortic diameter anterior to ABS	PT with PLDA = 70	PT alone = 118	Odds ratio	95% CI	P-value
0%–25%	7 (10%)	29 (25%)	0.34	0.14–0.83	**0.02**
25%–50%	26 (37%)	37 (31%)	1.30	0.70–2.41	0.42
50%–75%	18 (26%)	18 (15%)	1.92	0.92–4.00	*0.08*
75%–100%	19 (27%)	34 (29%)	0.92	0.48–1.78	0.81
• >50%	37 (53%)	52 (44%)	1.42	0.79–2.56	0.24

Table 3
Amount of left mainstem bronchial compression (LMSB) as noted on preoperative bronchoscopy. Patients who underwent a posterolateral descending aortopexy (PLDA) at the time of surgery were more likely to have >50% LMSB compression (PT = posterior tracheopexy).

Percent of left mainstem bronchial compression	PT with PLDA = 70	PT alone = 118	Odds ratio	95% CI	P-value
0%–25%	11 (16%)	55 (47%)	0.21	0.10–0.45	<**0.01**
25%–50%	12 (17%)	34 (29%)	0.51	0.24–1.07	*0.07*
50%–75%	24 (34%)	7 (6%)	8.27	3.37–20.53	<**0.01**
75%–100%	23 (33%)	7 (6%)	2.72	1.34–5.52	<**0.01**
• >50%	47 (67%)	14 (12%)	7.60	3.90–14.80	<**0.01**
Unknown	0 (0%)	4 (3%)	–	–	–

Table 4
Breakdown of the number of patients who underwent a posterior tracheopexy (PT) with posterolateral descending aortopexy (PLDA) based on year of surgery.

Year of surgery	PT with DA = 70	Percent of total
2012	2	3%
2013	2	3%
2014	3	4%
2015	4	6%
2016	26	37%
2017	33	47%

more likely to have received a PLDA at the time of TBM surgery (OR = 7.60, 95% CI = 3.90–14.80, $p < 0.01$) (Table 3).

As we have become more facile with the posterior tracheopexy procedure, we began to identify certain patients that had persistent symptoms despite posterior airway work; therefore, the posterolateral descending aortopexy has become a larger part of our repertoire to help alleviate airway compression in recent years, with only 11 of the 70 patients who received a PLDA undergoing surgery prior to 2016 (Table 4).

2.2. Multivariate analysis

Multivariate analysis was then performed to determine the most significant preoperative variables that were associated with the performance of a PLDA. History of EA, presence of great vessel anomaly, concurrent esophageal surgery, >50% LMSB compression, >50% of the aortic diameter located anterior to the ABS, and year of surgery were included. Using these variables, >50% LMSB compression (OR = 8.06, 95% CI = 3.62–17.95, $p < 0.001$) was found to be strongest and most significant predictor of undergoing a PLDA at the time of TBM surgery. The presence of >50% of the aortic diameter located anterior to the ABS (OR 2.06, 95% CI = 0.98–4.3, p = 0.05) and having had surgery in recent years (OR 1.61, 95% CI = 1.18–2.21, p = 0.003) were also found to be significantly associated with performing a PLDA (Table 5).

Table 5
Multivariable logistic regression analysis of significant univariable preoperative predictors of the performance of a posterolateral descending aortopexy (PLDA) at the time of surgery for tracheobronchomalacia.

Variable	Odds ratio	95% CI	P-value
History of esophageal atresia	1.30	0.52–3.27	0.57
Great vessel anomaly	1.43	0.58–3.55	0.44
Concurrent EA surgery	0.81	0.36–1.84	0.62
>50% Left mainstem bronchial compression	8.06	3.62–17.95	<**0.001**
>50% Aorta anterior to the spine	2.06	0.98–4.3	**0.05**
Year of surgery	1.61	1.18–2.21	**0.003**

Table 6
Location of the artery of Adamkiewicz among the study population.

Artery of Adamkiewicz	Number of patients	Percentage
Total number	40	100%
Above T5	1 (C6)	2.5%
T5	1	2.5%
T7	1	2.5%
T8	4	10%
T9	4	10%
T10	11	27.5%
T11	14	35%
T12	4	10%

2.3. Artery of Adamkiewicz

Of the 40 patients with a documented location of the takeoff of the AoA, the most common locations were at T11 ($n = 14$, 35%) and T10 ($n = 11$, 28%) but it was found to be as high as C7–T1 and as low as T12. Notably, 19 of the 40 patients (47.5%) had an AoA takeoff within the operative field (T10 or higher) (Table 6).

2.4. Clinical outcomes

The median operative time was not significantly different for patients who underwent a PT with PLDA (6:02 h; IQR 4:33, 7:58) compared to patients who did not have a PLDA (6:39 h; IQR 4:51, 8:34; p = 0.09), irrespective of the need for concurrent esophageal or cardiac procedures at the time of tracheopexy. The quicker OR times may indicate that as we have become more facile with posterior airway work, our times have decreased, and the addition of a posterolateral descending aortopexy does not add a significant amount of time to the overall procedure. The total complication rate was similar between patients who had a PT with a PLDA (29%) and those who had an isolated PT (21%, p = 0.22); however, the PLDA group had a greater rate of chyle leaks postoperatively (13% vs 2%, $p < 0.01$) (Table 7). All but one chyle leak resolved with either a nonfat diet or a period of parenteral nutrition; the one patient that did not heal the chyle leak expectantly required lymphatic sclerotherapy by interventional radiology for a persistent leak that likely failed to heal on its own owing to an associated large brachiocephalic thrombus that impeded the natural lymphatic drainage. There were no aortic or spinal cord injuries in patients who underwent a PLDA (Table 7).

A total of 51 (27%) patients required additional subsequent airway procedures. The majority of these patients ($n = 42$, 82%) who required further airway procedures also had anterior airway collapse that re-

Table 7
Postoperative complication rate between patients who underwent a posterolateral descending aortopexy (PLDA) at the time of posterior tracheopexy (PT) versus patients who just received a PT for treatment of symptomatic tracheobronchomalacia (ICU = intensive care unit, DVT = deep venous thrombosis).

	PT with PLDA ($n = 70$)	PT alone ($n = 118$)	p-value
Total complication rate	20 (29%)	25 (21%)	0.22
• Chyle leak	9 (13%)	2 (2%)	<**0.01**
• Diaphragm paralysis	2 (3%)	2 (2%)	0.59
• ICU readmission	2 (3%)	1 (1%)	0.31
• DVT	1 (1%)	3 (3%)	0.37
• Bilateral vocal cord paresis	2 (3%)	3 (3%)	0.90
• Unilateral vocal cord paresis	0 (0%)	4 (3%)	0.14
• Pneumothorax/pleural effusion[a]	2 (3%)	5 (4%)	0.63
• Superficial site infection	1 (1%)	1 (1%)	1.00
• *Clostridium difficile* infection	1 (1%)	4 (3%)	0.37
Additional airway procedures required	15 (21%)	36 (31%)	0.18
• Redo posterior airway work	3 (4%)	9 (8%)	0.36
• Anterior airway work	12 (17%)	30 (25%)	0.19
• New tracheostomy required	3 (4%)	5 (4%)	0.99

[a] Requiring new thoracostomy tube.

quired an approach via sternotomy with an anterior aortopexy and anterior tracheopexy support. There was no difference in need for anterior airway procedures or redo posterior airway work between patients with or without a PLDA (Table 7).

Ten (56%) of the 18 patients that were on mechanical ventilation (without a tracheostomy) and underwent a PT (with [$n = 6$, 67%] or without [$n = 4$, 44%] a PLDA, $p = 0.34$) owing to multiple prior failed extubation attempts were able to be discharged either on room air or <1 L nasal cannula. The remaining eight patients who were on mechanical ventilation preoperatively (PT with PLDA = 3, PT alone = 5, $p = 0.99$) went on to require a tracheostomy after tracheopexy: three for bilateral vocal cord paresis, two with type III or type IV laryngeal cleft, and three with subsegmental or distal small airway disease. Of 22 patients who had a tracheostomy prior to posterior tracheopexy, one (4.5%) was decannulated prior to discharge and nine (41%) were able to be weaned to tracheostomy collar or capping at the time of discharge, while the remainder were able to be weaned to lower ventilatory settings and are undergoing a gradual weaning process.

3. Discussion

Our study results suggest that preoperative variables (namely, >50% LMSB compression, and >50% of the aorta located anteriorly to the anterior border of the spine) are able to identify patients in whom one may consider the addition of a posterolateral descending aortopexy to a posterior tracheopexy at the time of surgical treatment of TBM. Our results also highlight that in up to half of the patients, the AoA may be located within the operative field; therefore, the procedure can only be safely performed when this knowledge has been established preoperatively to avoid the potential devastating consequences from spinal cord ischemia.

We do not advocate that a PLDA is necessary in all patients who need surgical treatment of tracheobronchomalacia but rather suggest that it be considered as an adjunct procedure to posterior tracheobronchopexy when extrinsic compression of the LMSB is present. The malacia that extends to the LMSB can be very challenging to manage, particularly from the right chest, but with the addition of a PLDA one can gain additional space to support the first and second portions of the LMSB on the left side of the spine. Despite this, we do not consider the issue of LMSB malacia resolved, as despite this approach, there are several patients in whom this approach was not enough and needed additional surgery. Understanding the relationship [1–24] that the descending thoracic aorta has with the LMSB and its potential pitfalls are particularly important as the posterior tracheopexy technique gains popularity and more and more surgeons are considering posterior tracheopexy as a treatment modality [18–21]. Our main concern is that LMSB compression should be thoroughly evaluated when considering patient selection and technique for posterior tracheopexy. If the LMSB is not addressed at the time of posterior tracheopexy, posterior tracheal membrane displacement may create additional extrinsic compression of the LMSB, leading to impaired gas exchange and airway clearance.

Upon review of the literature, Hungate also performed a retrospective review of MRIs of 10 children with symptomatic LMSB narrowing and compared the images to 40 children who did not have respiratory symptoms [22]. The percentage of the circumference of the descending aorta that was located anterior to the vertebral body at the level of the LMSB crossing was compared. While 60%–75% patients in each group had a descending aorta that was located either 25%–50% or 50%–75% anterior to the ABS, a significantly greater percentage of symptomatic patients had the entire circumference of the descending aorta located anterior to the ABS (40% vs 10%) [22]. Our study also showed similar findings, with univariate analysis identifying LMSB compression and aortic positioning to be significantly associated with performance of a PLDA. Likewise, patients who had either a ≤25% LMSB compression or <25% of the aortic diameter anterior to the ABS were more likely to receive just a posterior tracheopexy. This information is critical for surgical and anesthetic planning and patient counseling.

A recent study by Arcieri and colleagues in Italy reported results from a retrospective review of 18 patients with symptomatic LMSB narrowing who were treated with a descending aortopexy [23]. Their results showed relief of LMSB compression in 54% of patients with aortopexy alone. Similarly, our group has previously reported a cohort of 32 patients who underwent PT with PLDA and had significant improvement in symptoms, including cough, infections, oxygen requirements, and BRUEs [14]. The findings from these two papers are in line with our association of an anteriorly placed aorta contributing to LMSB compression and exacerbating TBM symptoms.

A well-known complication of surgery on the descending aorta, especially in adults with descending thoracic and thoracoabdominal aneurysm repairs, is ischemia of the spinal cord resulting from injury to the artery of Adamkiewicz, which occurs in 0.2%–8% in the adult population [24]. To prevent such complications, we have included an additional measurement when evaluating the CT angiogram — the level of the AoA. Using this measurement, one can further determine at what levels movement of the descending aorta is safe without risk to the AoA. During preoperative planning, location of the AoA often requires the identification of the “hairpin turn” after the intervertebral foramen, which can be isolated 80%–90% of the time [23]. In the adult population, the most common location of the AoA was between T9 and T11, with close to 90% found between T8 and T12 [16,24]. This corroborates with our study, as all but three patients had AoA that were within this range; however, the AoA also was found as high as C7–T1, and these outliers remind us of the importance of thorough preoperative planning, which allowed us to dissect the descending aorta while minimizing trauma and injury to the AoA and blood flow to the anterior spinal artery.

Limitations of this study include its single institution design and retrospective nature; however, a prospective comparative trial may not be feasible given the variability in TBM severity and location between patients which often requires patient-specific customized operative plans. Strengths of this study include the size of the cohort studied and the multivariate model used to account for confounding and collinear variables. Future direction would focus on validating this model and its variables with a prospective cohort of patients. Future research should also explore the long-term outcomes of this patient population, which is an area of active research for our group.

We caution that the true long-term benefit of adding a posterolateral descending aortopexy to a PT in terms of symptom resolution is not addressed by our data within this manuscript (although we have previously published on it) [14]. While our intent with this manuscript is to describe the rationale for when to consider a PLDA and to evaluate pertinent anatomic-related patient characteristics that predict the need for PLDA in order to better counsel our patients and improve surgical planning, we recognize that both long-term and short-term outcomes are necessary to truly evaluate the efficacy of the procedure. In our study, we were able to show that performance of a PLDA along with PT did not add significantly to the operative time, had similar overall complication rates (albeit greater risk of chyle leak), and had immediate dramatic benefits in some patients such as helping them to wean from mechanical ventilation and avoiding some tracheostomies. For example, the one patient who had his tracheostomy decannulated prior to discharge had a PT with a PLDA. The suggested thresholds established here of >50% LMSB collapse and >50% anterior location of the aorta with respect to the spine need to be further corroborated in prospective cohorts and at other institutions. Nonetheless we think these variables and thresholds identified in this study represent a starting framework, one that can provide a common language that can be useful when evaluating this challenging patient population.

4. Conclusion

It is critical to understand the interplay of the descending aorta, the anterior border of the spine, and the left mainstem bronchus in the evaluation of symptomatic tracheobronchomalacia patients. Chest CT angiography and dynamic tracheobronchoscopy are crucial elements of the preoperative evaluation. A posterolateral descending aortopexy in addition to posterior tracheobronchopexy should be considered in symptomatic patients with TBM who have >50% left mainstem bronchus collapse on active cough, and/or >50% of the aortic diameter located anterior to the anterior border of the spine. When performing a PLDA, preoperative identification of the level of the artery of Adamkiewicz is mandatory in order to avoid serious neurological sequelae at the time of surgery. Performing a PT with a PLDA is safe in experienced centers and can help address challenging LMSB malacia as evidenced by weaning from mechanical ventilation and extubation in select patients.

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