Journal of Pediatric Surgery 55 (2020) 1302–1308

Contents lists available at ScienceDirect

Journal of Pediatric Surgery

journal homepage: www.elsevier.com/locate/jpedsurg

Airway/Thoracic Conditions

Great vessel anomalies and their impact on the surgical treatment of tracheobronchomalacia☆,☆☆,★

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ARTICLE INFO

Article history:
Received 15 March 2019
Received in revised form 28 July 2019
Accepted 1 August 2019

Key words:
Great vessel anomalies
Aortic arch anomalies
Tracheobronchomalacia (TBM)
Esophageal atresia
Tracheopexy
Tracheobronchial compression (TBC)

ABSTRACT

Background: Tracheobronchial compression (TBC) from great vessel anomalies (GVA) can contribute to tracheobronchomalacia (TBM) symptoms. The frequency, impact on symptoms and optimal management of GVA in these patients, with or without a history of esophageal atresia (EA), are still unclear.
Study design: Patients who underwent surgery for TBM/ TBC between 2001 and 2017 were reviewed. Demographics, type of GVA, and operative interventions were collected. The frequency and treatment modalities of GVA between EA and non-EA patients were compared.
Results: Overall, 209 patients met criteria; 120 (57.4%) patients had at least one GVA, including double aortic arches (n = 4, 1.9%), right aortic arches (n = 14, 6.7%), aberrant right subclavian arteries (n = 15, 7.2%), and innominate artery compression (n = 71, 34.0%). Non-EA patients were more likely to have surgery later in life (29.5 months versus 16 months, p = 0.0002), double aortic arch (p = 0.0174), right aortic arch (p < 0.0001), and undergo vascular reconstruction concurrently with their airway procedure (25% vs 8.4%, p = 0.002). Vessel reconstruction was performed in 25 patients; six required cardiac bypass.
Conclusion: The frequency of GVA in patients with symptomatic airway collapse is substantial. Multidisciplinary evaluation is imperative for operative planning as many require complex reconstruction and collaboration with cardiac surgery, particularly patients without a history of EA.
Level of evidence: Level III.

Tracheobronchomalacia (TBM) is an excessive dynamic collapse of the airway that may be associated with a congenital anomaly such as esophageal atresia (EA), while tracheobronchial collapse (TBC) is because of vascular compression by anomalous great vessels. TBC from aberrant great vessel intrusion and TBM from airway maldevelopment are structurally different but can occur concurrently in the same patient; consequently, relief from the compression of the great vessels may still leave residual TBM in the same area, or TBC and TBM may affect different parts of the airway. Other associations with TBM include prolonged intubation, cystic fibrosis, prematurity, and connective tissue disorders. [1–6] The presentation of TBM and TBC is broad; some patients are asymptomatic, while others may have nonspecific symptoms, such as chronic cough, exercise intolerance, wheezing, or recurrent respiratory infections. [6–8] In more severe cases, patients may suffer from BRUEs (brief resolved unexplained events that include cyanosis, irregular breathing, and altered consciousness), the inability to wean from mechanical ventilation, or the inability to successfully undergo tracheostomy decannulation. [1,9]

The frequency of TBM in patients with a history of EA has been reported to range anywhere from 10% to 75%, [7,10,11] while the frequency of great vessel anomalies (GVA) reported in patients with a history of EA ranges from 5% to 18%. [12–14] Though it is unclear what proportion of these patients with GVA and a history of EA present with symptomatic TBM, the reported frequency of GVA in patients with TBM but without a history of EA ranges between 18% and 50%. [15,16] However, these series are limited in the number of patients evaluated (some in the single digits). Given that patients with TBM who do and do not have a history of EA are very different patient populations, examining these patients in isolation provides an incomplete picture of the problem. More importantly, the optimal diagnostic and treatment

☆ Declarations of Interest: none
☆☆ Funding Source: This research did not receive any specific grant from funding agencies in the public, commercial, or non-for-profit sectors.
★ Meeting Presentation: This paper was submitted in abstract form to the American Thoracic Society 2018 International Conference and presented as a poster presentation.

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https://doi.org/10.1016/j.jpedsurg.2019.08.001
0022-3468/

algorithm for these complex patients remains unclear. Similarly, the spectrum of presentation for patients with TBM and TBC is quite broad, often necessitating a tailored surgical approach, for which the precise location and cause of airway collapse, particularly if it is compounded by extrinsic vascular compression, become a crucial part of the preoperative planning.

In order to better understand the impact of GVA on patients with symptomatic TBM, we sought to characterize and examine the frequency of GVA in patients with symptoms of TBM, to compare the types of GVA between patients with TBM and TBC who do and do not have a history of EA, and to examine the different treatments employed to relieve the airway compression from GVA in such patients. We hypothesized that patients with pure TBM/ TBC (without EA) would have a greater frequency of great vessel anomalies that led to symptoms and that they would require more complex vascular surgical reconstructions and additional airway procedures to relieve the airway compression.

1. Materials and methods

1.1. Study design

This study was approved by Boston Children's Hospital Institutional Review Board (IRB #P00004344); informed consent was waived owing to the retrospective nature of the study. A retrospective chart review was performed of all patients within the Esophageal and Airway Treatment Center database who underwent surgery for symptoms of TBM from July 2001 to December 2017. Patients who underwent a multidetector computed tomography (MDCT) angiogram of the chest prior to surgery were included for potential analysis. Those who presented with outside hospital radiographic studies or without an official radiology report from our institution were excluded, as the official radiology report of the great vessel anatomy used to standardize the classification of great vessel anomalies was not available.

1.2. Preoperative workup

In addition to MDCT, the evaluation of suspected TBM also includes a 3-phase dynamic rigid tracheobronchoscopy to delineate the degree of airway collapse. The 3 phases are intended to evaluate 1) the degree of static collapse of the airway during normal shallow breathing, 2) the degree of dynamic collapse with forced exhalation or coughing, and 3) anatomic abnormalities such as diverticuli, fistulas, or aberrant branching, which are best seen with airway distention maneuvers. [1–4,11] The degree of anterior compression from a great vessel anomaly can be best seen during normal breathing with persistence noted during airway distention.

At our institution, MDCT imaging using a reduced dose of radiation has been performed since August of 2007. [5] Early imaging was done in both the inspiratory and the expiratory phase using either a 16-detector scanner or a 64-detector scanner; the 64-detector scanner was used for all patients imaged after August 2007, using a protocol for dynamic airway imaging and identification of the Artery of Adamkiewicz. The reference tube current was based on the patient's weight when using the 16-detector scanner and based on the patient's age when using the 64-detector scanner. Inspiratory imaging was performed using the reference tube current levels, while a 50% reduction of tube current was used during the expiratory phase, leading to approximately at 23% reduction in radiation exposure compared to standard dosing. [5] 4-D reconstruction of the airway was performed with each study.

Surgical repair was offered to patients with severe respiratory symptoms (e.g. frequent respiratory infections, recurrent pneumonias, presence of BRUEs, or inability to wean from mechanical ventilation) and >75% collapse of the trachea or mainstem bronchi. The type of surgical intervention performed was determined in part by the degree of posterior tracheal membranous intrusion versus anterior compression from anomalous great vessels.

1.3. Data collection

Patients were divided into two categories based on whether the patient had a history of esophageal atresia. Demographics, including sex, gestational age, history of prematurity, structural cardiac defects, presence of a laryngeal cleft, presence of a tracheostomy prior to surgery, and age at surgery were recorded. The frequency of different great vessel anomalies was identified and classified based on the Congenital Heart Surgery Nomenclature and Database Project manuscript that was published by Backer and Mavroudis. [17] [Fig. 1a–e] Therefore, the classification of a double aortic arch was subdivided into a right dominant arch, a left dominant arch, or balanced arch; a right aortic arch was further separated into patients with a right aortic arch and retroesophageal left subclavian artery, a right arch with mirror-branching pattern, or a right arch with a circumflex aorta. Other great vessel anomalies that were captured included an aberrant right subclavian artery, innominate artery compression, and/or pulmonary sling. [17] Other variations in great vessel anatomy, including an aberrant insertion of the carotid or vertebral arteries, were identified under an "other" category. The prevalence of bovine aortic arches (common origin of the innominate artery and left carotid artery onto the aortic arch) was also captured. Innominate artery compression was defined as a "fixed tracheal narrowing in the region of the innominate artery crossing," as determined by the official radiologist's interpretation.

For patients with great vessel anomalies, the operative reports were searched to determine if and what type of vascular reconstruction was performed at the time of surgery for TBM. Backer et al. published two articles standardizing the nomenclature used to describe great vessel anomalies [17,18]. Operations that appropriately relieve patient symptoms are also described alongside the anatomic description. In discussion with our pediatric cardiac surgeons, we have used this reference to help determine the best operative approach for each great vessel anomaly.

1.4. Statistical analysis/calculation

Descriptive and summary statistics are provided when applicable. The frequency of great vessel anomalies and aberrant vessels was compared between patients with symptomatic TBM/ TBC with and without a history of EA using Fisher's exact test, where a $p < 0.05$ was considered statistically significant. Statistical analyses were carried out in Microsoft® Excel® 2016 (Redmond, WA).

2. Results

In our Esophageal and Airway Treatment Center database, 320 patients had MDCT imaging of the chest between 2001 and 2017. Of these, 28 were excluded for the following reasons: outside hospital scans ($n = 19$) and no great vessel anatomy documented ($n = 9$), leaving 292 eligible patients for our study cohort. Of these patients, 209 (71.6%) underwent surgery for symptoms of TBM. Patients were then grouped according to whether they had a history of esophageal atresia or not. Patients with a history of EA underwent either isolated airway surgery or airway surgery concomitantly with esophageal work, often in a reoperative setting. One hundred and fifty-seven patients were noted to have a history of esophageal atresia (75.1%), while 52 patients did not have esophageal atresia and were classified as patients with only tracheobronchomalacia or airway compression (24.9%). [Fig. 2] When comparing demographics, there was a similar proportion of male patients (58.6% vs 61.5%, $p = 0.71$), and patients presenting with a tracheostomy prior to surgery for TBM (10.8% vs 17.3%, $p = 0.22$); there was also a similar frequency of structural cardiac defects (33.1% vs 25%, $p = 0.28$) and of a persistent left SVC between the two groups

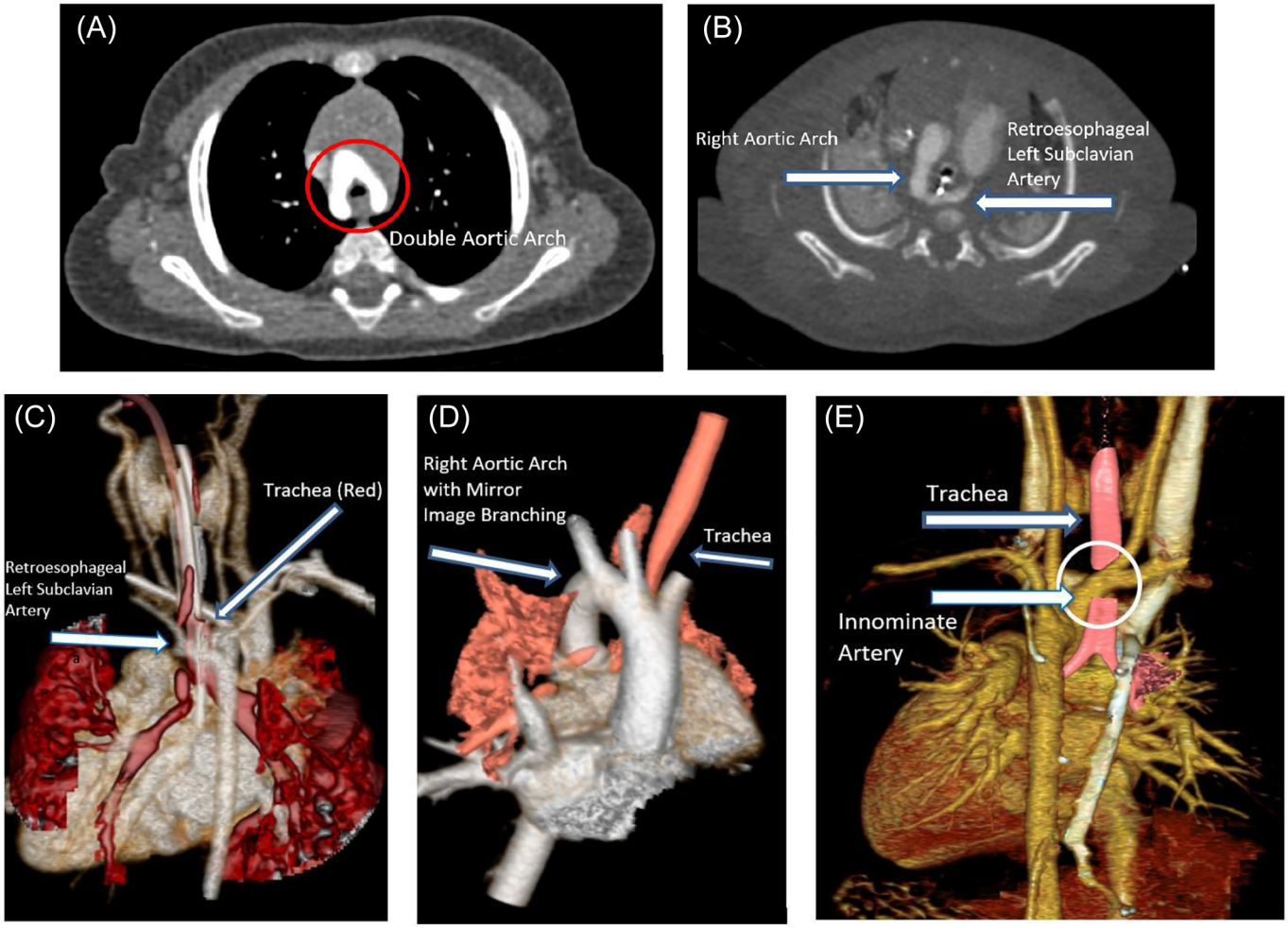

Fig. 1. (A–E) Axial CT and 3D reconstructed images of great vessel anomalies identified. (A) Axial imaging of a balanced double aortic arch as it surrounds the trachea. (B) A patient is noted to have a right aortic arch with a retroesophageal left subclavian artery on axial CT, whose relationship to the trachea is better identified on 3D reconstruction (C). (D) This patient has a right aortic arch with mirror image branching that can best be seen with 3D reconstruction. (E) The posterior view of a MDCT scan with 3D reconstruction shows significant innominate artery compression, causing complete collapse of the mid trachea (T2).

(14.0% vs 5.8%, p = 0.12). The esophageal atresia cohort had a significantly greater proportion of patients born prematurely (52.2% versus 32.7%, p = 0.01) and who were found to have a laryngeal cleft (35.0% versus 19.2%, p = 0.033). The cohort with only TBM, or non-EA, underwent surgery for TBM at an age that was significantly older than the EA cohort (median age: 29.5 months versus 16 months, p = 0.0002) [Table 1].

In 120 patients (57.4%), at least one great vessel anomaly was encountered. The most common anomalies were innominate artery compression (n = 71, 34.0%), bovine aortic arch (n = 27, 12.9%), aberrant right subclavian artery (n = 15, 7.2%), and right aortic arch (n = 14, 6.7%). There was no difference between the two groups in the percentage of patients with at least one great vessel anomaly (56.1% for the EA group versus 61.5% for the non-EA group, p = 0.50), or in the percentage with innominate artery compression (35.0% versus 30.8%, p = 0.58), bovine aortic arch (15.3% versus 5.8%, p = 0.08), or aberrant right subclavian artery (7.6% versus 5.75%. p = 0.65) [Table 2]. However, the non-EA cohort had a significantly greater percentage of patients with a double aortic arch (5.8% versus 0.6%, p = 0.02), with a right aortic arch (21.2% versus 1.9%, p < 0.001), and with other great vessel anomalies (17.3% versus 6.4%, p = 0.02), which included an anomalous origin of left vertebral artery from the aortic arch and an anomalous innominate artery origin, among others compared to the EA cohort, respectively [Table 2].

The rates of posterior airway work (posterior tracheopexy, posterior mainstem bronchopexy, and/or posterior descending aortopexy), of anterior airway work (anterior direct tracheopexy, anterior ascending aortopexy, and/or innominate arteriopexy), and of requiring multiple sequential airway procedures were the same between the EA and non-EA cohorts. However, a significantly greater percentage of patients in the non-EA cohort underwent simultaneous anterior and posterior airway work during their first procedure (21.2% versus 3.2%, p < 0.001); these patients also were more likely to undergo vascular procedures to relieve airway compression at the same time as their surgery for TBM (25% versus 8.3%, p = 0.002) [Table 3].

Out of the 120 patients with a great vessel anomaly and TBM/TBC, 25 patients (20.9%) underwent combined cardiovascular and TBM procedures. Three patients underwent combined procedures concurrently with atrial septal defect or ventricular septal defect repair. A separate four patients (2 with a double arch, 2 with a right arch and mirror image branching) underwent great vessel anomaly repair at an outside facility but were referred for persistent respiratory symptoms and underwent isolated surgery for TBM. Eighteen cases were performed with pediatric cardiac surgery; six of these cases required cardiopulmonary bypass in order to relieve the TBC caused by the great vessel anomaly [Fig. 3].

The surgical procedures employed for a double aortic arch, a right arch with retroesophageal left subclavian artery, an aberrant right

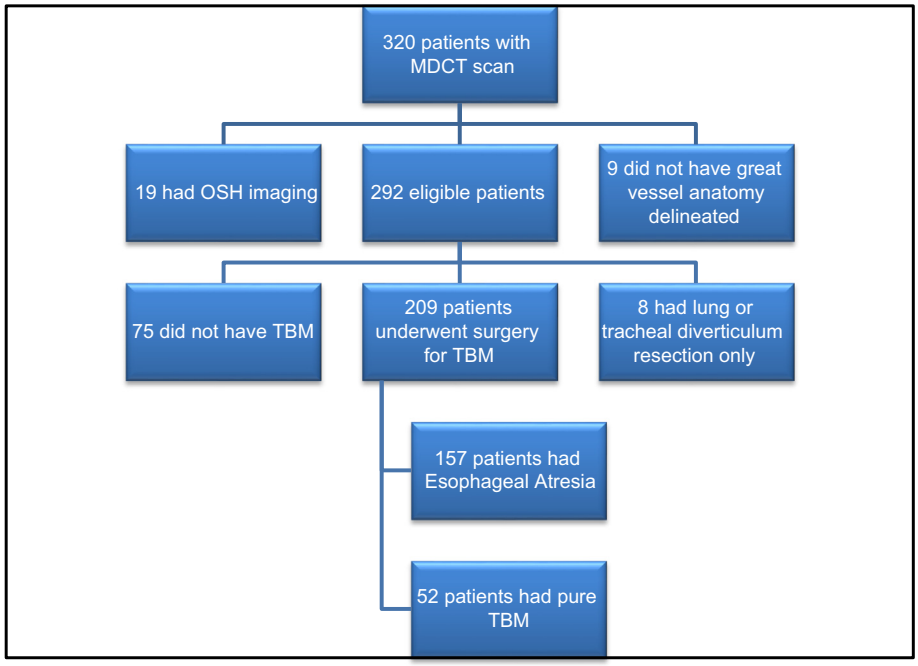

Fig. 2. Flowchart depicting the patient selection.

subclavian artery, and a circumflex aorta are best shown in Fig. 3. Unique cases included one patient who underwent a sternotomy for surgical repair of TBM with TBC owing to an aberrant right subclavian artery, while an aortic uncrossing procedure on cardiopulmonary bypass was performed in another patient with an aberrant left subclavian artery who also had right pulmonary agenesis. A third patient with a right aortic arch, right descending aorta and mirror image branching underwent a left thoracotomy with ductal ligament and diverticulum of Kommerell division combined with posterior tracheopexy.

Of the 22 patients who underwent concomitant great vessel anomaly and tracheobronchomalacia repair, five patients (22.7%) had undergone surgery at an outside facility for respiratory symptoms and repair of the great vessel anomaly prior to referral at our institution, while five patients (22.7%) required additional surgery at our institution for relief of persistent symptoms. Five patients were lost to follow-up after discharge, leaving 17 patients (77.3%) who have been followed for a median of 18.9 months (range: 10.6–41.2 months). All but two patients (15/17, 88.2%) or had no respiratory symptoms at their most recent follow-up. Only one patient with a previously repaired great vessel anomaly (vascular ring associated with a right aortic arch) who underwent isolated airway surgery at our institution required multiple airway procedures given his challenging airway. After an initial posterior tracheobronchopexy, the patient continued to be symptomatic with recurrent right-sided pneumonias and dyspnea on exertion owing to persistent right mainstem bronchial collapse. The patient subsequently underwent a posterior descending aortopexy for TBC with right mainstem bronchopexy for TBM through a right thoracotomy and then an anterior aortopexy with an anterior direct tracheorbronchopexy through an upper median sternotomy for residual TBM. The patient is current symptom-free at two months after his most recent airway procedure.

3. Discussion

Our results highlight the substantial prevalence of great vessel anomalies in patients with symptomatic airway collapse for TBC and TBM. This is significant as knowledge of the presence of one of these great vessel anomalies may alter surgical management, especially in patients without EA, as these patients more often required vascular surgery for relief of TBC concomitantly with surgery to relieve TBM. In this patient population, understanding the relationship of the great vessels to the airway aids in planning the appropriate surgical exposure

Table 1
Demographics of symptomatic TBM patients comparing patients with a history of EA with patients who did not have EA.

Demographics	Total Cohort N = 209	EA Patients N = 157 (75.1%)	Non-EA Patients N = 52 (24.9%)	P-value
Male	124 (59.3%)	92 (58.6%)	32 (61.5%)	0.7128
Hx of Prematurity (≤36 weeks)	99 (47.4%)	82 (52.2%)	17 (32.7%)	***0.01***
Hx of Extreme Prematurity (≤30 weeks)	18 (8.6%)	12 (7.6%)	6 (11.5%)	0.3850
Structural Cardiac Anomaly	65(31.1%)	52 (33.1%)	13 (25%)	0.2752
➔ DORV, ToF, Ebstein's, TAPVR	➔ 15 (9.7%)	➔ 10 (19.2%)	➔ 5 (38.5%)	0.1426
➔ ASD, VSD	➔ 50 (40.3%)	➔ 42 (80.8%)	➔ 8 (61.5%)	0.1426
Persistent Left SVC	25 (12.0%)	22 (14.0%)	3 (5.8%)	0.1151
Age at Surgery (months), median (range)		16 (0–269) months	29.5 (1–210) months	***0.0002***
Age at Surgery (years), median (range)		1.3 (0–22.4) years	4.6 (0–17.6 years)	
Trach Prior to Surgery	26 (12.4%)	17 (10.8%)	9 (17.3%)	0.2191
Laryngeal Cleft	65 (31.1%)	55 (35.0%)	10 (19.2%)	***0.033***

Hx = history, DORV = double outlet right ventricle, ToF = tetralogy of Fallot, TAPVR = total anomalous pulmonary venous return, ASD = atrial septal defect, VSD = ventricular septal defect, SVC = superior vena cava.

Table 2
Comparison of incidence of specific great vessel anomalies between patients with a history of esophageal atresia and tracheomalacia and those with only tracheomalacia.

GV Anomaly	Total Cohort N = 209	EA Patients N = 157 (75.1%)	Non-EA Patients N = 52 (24.9%)	P-value
Total Number of GV Anomalies	150	105	45	
Number of Patients with at least one GV Anomaly	120 (57.4%)	88 (56.1%)	32 (61.5%)	0.4959
Double Aortic Arch	4 (1.9%)	1 (0.6%)	3 (5.8%)	***0.0174***
→ Right Arch Dominant	3	1	2	
→ Left Arch Dominant	0	0	0	
→ Balanced Double Arch	1	0	1	
Right Arch/Left Ligament	14 (6.7%)	3 (1.9%)	11 (21.2%)	< ***0.0001***
→ Retroesophageal Left Subclavian Artery	7	2	5	
→ Mirror Image Branching	5	1	4	
→Circumflex Aorta	1	0	1	
→ Anomalous Brachiocephalic	1	0	1	
Aberrant Right Subclavian	15 (7.2%)	12 (7.6%)	3 (5.7%)	0.6452
Innominate Artery Compression Syndrome	71 (34.0%)	55 (35.0%)	16 (30.8%)	0.5803
Bovine Arch	27 (12.9%)	24 (15.3%)	3 (5.8%)	0.0776
Pulmonary Sling	0	0	0	
Other Anomalies	19 (9.1%)	10 (6.4%)	9 (17.3%)	***0.0182***
→ Left vertebral artery origin from aortic arch	8	4	4	
→ Left arch, remnant ductal ligament	2	1	1	
→ Right aortosubclavian collateral	1	1	0	
→ Left arch, Left subclavian artery	1	1	0	
→ Left arch, circumflex aorta	2	2	0	
→ Aberrant ductal ligament from MPA to brachiocephalic trunk	1	0	1	
→ Four vessel arch	1	1	0	
→ Anomalous brachiocephalic/ innominate artery	4	1	3	

(right or left posterior thoracotomy, median sternotomy, and/or neck dissection) and raises awareness of the importance of collaboration with pediatric cardiac surgery. For example, in our cohort, the majority of patients with a double aortic arch, right aortic arch, or aberrant right subclavian vessel required vascular reconstruction with or without cardiopulmonary bypass for relief of TBC.

While studies have looked at the incidence of great vessel anomalies in patients with esophageal atresia or looked at the improvement of symptoms of airway collapse after vascular ring repair, no study has compared the frequency and type of great vessel anomalies in patients with EA versus patients with pure tracheomalacia or tracheobronchial compression and without EA. Berthet et al., Allen et al., Canty et al., and Mellins and Blumenthal all report between a 10% and 18% frequency of great vessel anomalies among the EA population [12–14,19]. This corresponds to our findings of a 16.5% frequency of aortic arch or aberrant subclavian vessel anomalies in this population but does not account for the high frequency of innominate artery compression that we found (35%). Some discrepancy may be because of the imaging techniques used for the diagnostic workup. In Berthet's study, the diagnostic workup included only echocardiograms and esophagrams, while in Allen's study, only echocardiograms were used. [12,13] This was a limitation proposed by Allen and colleagues, who found that echocardiograms only correctly identified a right aortic arch in 62.5% of patients. [12] While an echocardiogram can be helpful in diagnosing some great vessel anomalies, it is operator dependent, and it does not capture the full breadth of variations in great vessel anatomy or their impact on the airway. [20] For instance, both an echocardiogram and an esophagram are studies which can miss innominate artery compression, which is known to cause significant airway compression (TBC) and respiratory symptoms. At least 30% of patients in both groups of our study who underwent surgery for TBM were found to have innominate artery compression, making this the most frequent anomaly identified. Our findings of a greater than 50% incidence of great vessel anomalies in each cohort support those that Rogers et al. encountered, where half of their patients with TBM (no EA) had great vessel anomalies. [15] Of all the great vessel anomalies found in his study, innominate artery compression was also the most common anomaly encountered with four out of six patients that required surgery for airway collapse also found to have significant (> 70% luminal compression) innominate artery compression. [15]

Dynamic bronchoscopy is considered the gold standard for diagnosing TBM, while a multidetector computed tomography scanner with angiographic acquisition (MDCT angiogram) can be used to diagnose TBC with reasonable accuracy. [3,5,21] In the past, this involved obtaining images in both the inspiratory and expiratory phase in order to measure the change in tracheal lumen diameter during breathing. [5,22] In children, this strategy is an unreliable method of assessing airway dynamic collapse as they either will not cooperate with coughing and/or are often sedated and intubated to facilitate the MDCT. Our institution has adopted a dynamic airway CT protocol that has reduced radiation dosing and can provide both airway and vascular information in the same study, the specifics of which have been previously reported. [5] This alleviates the need for intubation in patients who are unable to follow commands, while still providing adequate images of the airway and great vessels. However, the real value of the MDCT lies in identifying the great vessels and other structures surrounding the airway and to define the influence of these structures on the trachea and mainstem bronchi. This essentially provides a blueprint for surgical planning as cases for TBM with associated great vessel anomalies causing TBC may require a multidisciplinary approach that may include vascular reconstruction and cardiopulmonary bypass capabilities.

The most common vascular anomalies that have been described include a double aortic arch, right aortic arch with retroesophageal left subclavian artery, right arch with circumflex aorta, left aortic arch with aberrant right subclavian artery, innominate artery compression, and pulmonary artery sling. [4,17,18] The approach to the correction of TBC caused by great vessel anomalies is driven by both the anatomy and any other planned additional procedures (i.e. need for concurrent esophageal work). In our practice, we try to get maximum benefit from a single incision, so most patients receive a posterior thoracotomy on the opposite side of their dominant arch. This facilitates double arch

Table 3
Comparison of the different types of airway procedures performed between the EA and non-EA group.

Operations	Total Cohort N = 209	EA Patients N = 157 (75.1%)	Non-EA Patients N = 52 (24.9%)	P-value
Posterior Airway Work	130 (62.2%)	102 (65.0%)	28 (53.8%)	0.1498
Anterior Airway Work	19 (9.1%)	17 (10.3%)	2 (3.8%)	0.1501
Simultaneous Posterior and Anterior Airway Work	16 (7.7%)	5 (3.2%)	11 (21.2%)	<***0.0001***
Staged or Multiple Separate/Sequential Procedures for TBM	44 (21.1%)	33 (21.1%)	11 (21.2%)	0.9878
Patients with Concurrent Vascular Procedures along with TBM Surgery	26 (21.4%)	13 (8.3%)	13 (25%)	***0.002***

Posterior work indicates posterior tracheopexy, mainstem bronchopexy, and/or posterior descending aortopexy. Anterior work indicates anterior direct tracheopexy and/or anterior aortopexy.

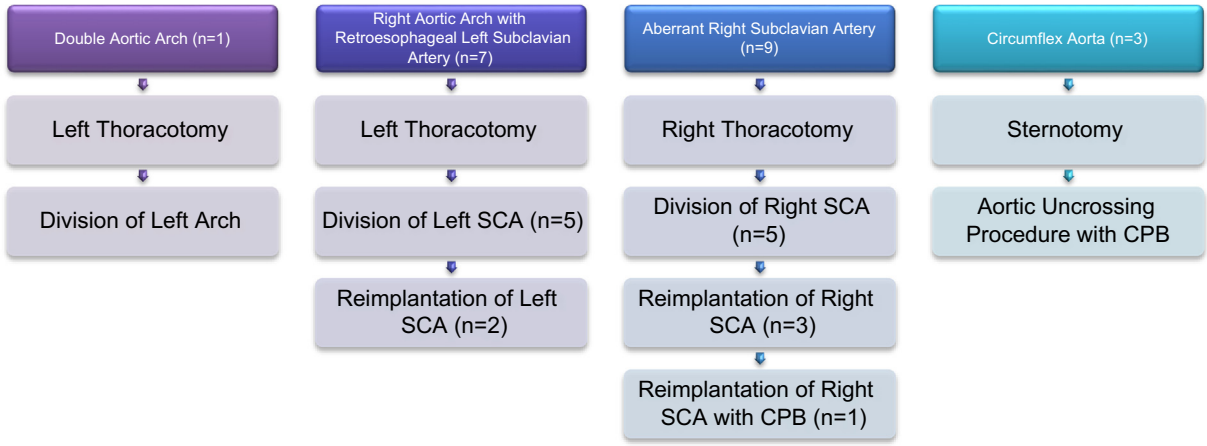

Fig. 3. Flowchart describing the most common vascular procedures performed based on the type of great vessel anomaly encountered at the time of surgical correction of tracheobronchomalacia. In patients with an aberrant subclavian artery (left or right), if the blood pressure dropped >10 mmHg in the left arm after manipulation of the subclavian artery, the artery was reimplanted (SCA = subclavian artery, CPB = cardiopulmonary bypass).

division, resection of diverticulum of Kommerell, ductal ligament division if indicated, and aberrant subclavian artery division and reimplantation (if needed) for TBC, [16,23] as well as esophageal rotation and posterior tracheopexy for the treatment of excessive posterior membrane intrusion as the cause of TBM. An anterior approach facilitates arch reconstruction or aortic uncrossing procedures, repair of pulmonary artery sling, ductal ligament division, as well as providing access for repair of structural congenital heart defects. [18] This anterior approach through a median sternotomy also is used to anteriorly move and directly support the ascending aorta, innominate artery, pulmonary artery, the trachea, and the bilateral mainstem bronchi. [20,23,24] As the malformed tracheal rings will often maintain their abnormal restrictive shape after vascular elevation, a direct tracheobronchopexy to the sternum or anterior structures of the neck is often required to open the airways. The effects of suture placement and tightening must be closely monitored intraoperatively by flexible fiberoptic bronchoscopy typically done by the anesthesia team to achieve optimum results without creating an airway deformity.

In patients with vascular rings or aberrant great vessel anatomy, anterior relief of the vascular compression can help improve the respiratory symptoms of patients. In Ruzmetov's study, 75% of patients were free from compressive symptoms at one year. [25] Naimo's study reported 86% of patients being free from respiratory symptoms at a median of 11.4 years postoperatively after vascular ring repair; these results are similar to our study, where 88% of patients that were followed after discharge had either improved or complete relief of symptoms. However, Naimo also reported that 14% of patients still demonstrated persistent respiratory symptoms at long-term follow-up, and one patient required a tracheostomy in the short-term following surgery owing to persistent TBM. [16] This is lower than our study, where 9/29 (31%) of patients were referred to our institution for persistent symptoms after initial procedures for great vessel anomalies were performed at outside facilities.

One reason for patients having continued symptoms despite GVA repair for TBC could be the simultaneous presence of dynamic or static posterior intrusion of the trachea owing to a widened posterior membrane forming a “U” or “bow” shaped cartilages along with great vessel anomalies (TBM). In our population, posterior airway work was performed in >50% of patients in both the EA (65%) and non-EA groups (53.8%), with no significant difference between the groups. Therefore, both the preoperative dynamic 3-phase bronchoscopy, which evaluates the amount and location of posterior intrusion (TBM), and the MDCT with angiogram, which identifies the location and effect of great vessel anomalies and other sites of compression (TBC) on the airway, are valuable to help determine which approach will provide the most symptomatic relief. In some patients, two or more operations may be required to optimally open the airways, as was seen in approximately one-fifth of patients. In these challenging cases, it is our preference to approach the airway posteriorly first, if possible. If symptoms fail to improve or do not improve enough, a repeat evaluation with dynamic bronchoscopy is performed. If persistent substantial anterior intrusion is encountered, we then proceed with anterior airway work and any vascular reconstruction that was not treated previously can now be addressed via a partial upper sternotomy, which often includes a thymectomy to gain space in the mediastinum and provides room to move structures compressing the airway. Of note, while the numbers are small, there were a significantly greater percentage of non-EA patients who underwent both posterior and anterior work during their initial surgery (21.1% versus 3.1%). In these cases, a posterior tracheopexy through a thoracotomy was performed first. If significant intrusion still existed on intraoperative bronchoscopy, the decision was made to proceed with anterior airway work via a partial upper median sternotomy while under the same anesthetic. However, in patients who require complex aortic or vascular reconstruction, both posterior and anterior airway work can be performed through a full vertical median sternotomy incision, although this is technically more challenging. Aberrant subclavian arteries, which often course posteriorly to the trachea, can prevent the appropriate performance of a posterior tracheopexy. If mobilization alone of the aberrant subclavian artery is not enough to allow for complete relief of the intrusion on the airway, a test clamp is placed at the take off from the aortic arch, and the respective extremity's arterial perfusion is monitored via an arterial line tracing. If the mean arterial pressure does not drop more than 10 points from the baseline, or preclamp state, then the artery is divided; conversely, if there is a substantial drop in that extremity's blood pressure, the artery is reimplanted elsewhere.

Limitations of this study include its retrospective nature and single institution design. We are a large referral center, so there is a referral and selection bias inherent to our practice. Many of our patients have already undergone previous airway and/or cardiovascular procedures elsewhere and come to us for persistent symptoms. Hence, our findings may not be applicable to the general population or to other practice settings; nonetheless, this allows us to evaluate a large number of patients and harness this collective experience. As a result, this is the largest pediatric study focusing on the identification and management of aberrant or anomalous great vessel anatomy in patients with symptoms of TBM and TBC.

Furthermore, it is also the first study to compare the frequency of great vessel anomalies between EA and non-EA patients, both of whom can present with symptoms of TBM. Though the main purpose of this work was to

highlight the operative evaluation, patient selection and describe the impact of great vessel anomalies in patients with TBM, we recognize that without patient outcome data, our assessment is incomplete. We have previously reported on some of our patient outcome measures [26–28], and this study does provide more prolonged follow-up for patients than had been previously reported. Further research is still needed in this area to explore the postoperative results of surgery for TBM in terms of long-term symptom relief. Although venous anomalies may not directly cause airway compression, they are important in surgical planning and their variations need to be considered when placing central venous lines in these patients. Anatomic variants, such as bovine arches and persistent left SVCs, both of which were found with some regularity, especially in the EA population, should be further evaluated in terms of the changes in surgical technique required to accommodate these variants in patients undergoing surgical correction of TBM. Collaboration and formation of a multicenter or multinational database compiling data on all patients evaluated for tracheobronchomalacia will also help to define the prevalence of great vessel anomalies among the larger population of patients with TBM.

Advances in 3D and 4D reconstruction and dynamic components (images in different breathing phases) to CT imaging have improved our abilities to visualize the relationship of great vessel anomalies to the airway, which become helpful in facilitating conversations with parents and healthcare providers about the perceived surgical challenges and intended operative approach. While we have been able to decrease the dose of radiation used during these scans, the risks of radiation still exist. The use of MRI is frequent in the pediatric population as a method of reducing radiation exposure when detailed imaging is required; however, the utility of MRI for diagnosing TBM or determining the impact of great vessel anomalies on airway compression has not been established. Future research could look at the feasibility and accuracy of MRI in comparison with MDCT. The use of MDCT with 3D printing of challenging airways with great vessel anomalies to allow for simulated repairs or to help optimize potential surgical approaches is another avenue of future research in this area.

4. Conclusions

In patients with symptomatic airway collapse from TBM and TBC, great vessel anomalies, particularly innominate artery compression, are very common. An MDCT with angiogram, for the identification of these great vessel anomalies and a 3-phase dynamic bronchoscopy are complementary and crucial for optimizing patient selection and preoperative planning. This is especially important in symptomatic airway patients without a history of EA, as these patients were more likely to have a double aortic arch, right aortic arch, or other vessel anomaly that led to significantly more combined airway and vascular procedures for appropriate symptom relief. A complete multidisciplinary evaluation and correlation with clinical signs and symptoms must be used to select TBM/TBC patients who can most benefit from surgical intervention.

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