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ORIGINAL ARTICLE

Anatomical study of the thoracic duct and its clinical implications in thoracic and pediatric surgery, a 70 cases cadaveric study

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Abstract

Introduction Given the high variability and fragility of the thoracic duct, good knowledge of its anatomy is essential for its repair or to prevent iatrogenic postoperative chylothorax. The objective of this study was to define a site where the thoracic duct is consistently found for its ligation. The second objective was to define an anatomically safe surgical pathway to prevent iatrogenic chylothorax in surgery for aortic arch anomalies with vascular ring, through better knowledge of the anatomical relationships of the thoracic duct.

Methods Seventy adult formalin-fixed cadavers were dissected. The anatomical relationships of the thoracic duct were reported at the postero-inferior mediastinum, at levels T3 and T4.

Results The thoracic duct was consistently situated between the left anterolateral border of the azygos vein and the right border of the aorta between levels T9 and T10, whether it was simple, double, or plexiform. It was located medially, anteromedially, or posteriorly to the left subclavian artery in 51%, 21%, and 28% of the cases, respectively, at the level of T3. At T4, it was posteromedial in 27% of the cases or had no direct relationship with the aortic arch.

Conclusion These results favor mass ligation of the thoracic duct at levels T9–T10 between the right border of the aorta and the azygos vein, eventually including the latter. To prevent iatrogenic postoperative chylothorax in aortic arch anomalies with vascular ring surgery, we recommend remaining strictly lateral to the left subclavian artery at the level of T3 to reach the aortic arch anomalies with vascular ring at T4.

Keywords Anatomy · Pediatric surgery · Chylothorax · Thoracic duct · Thorax · Anatomical variations

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Introduction

The thoracic duct (TD) is the largest lymphatic vessel in the body. It collects the lymphatic fluid from almost all of the minor lymphatic vessels, resulting in drainage of 75% of the body's lymph [1, 27]. Drainage of the right part of the head, the neck, and the superior hemithorax is performed by the right lymphatic duct [14].

Previous studies have described the main pathway of the TD: It begins at the convergence of the lumbar and intestinal lymph trunk, at the level of L1–L2, on the right posterolateral side of the aorta. It then ascends through the diaphragmatic aortic hiatus, on the right side of the vertebral column, and reaches the posterior mediastinum between the descendant aorta on its left and the azygos vein on its right [10, 14, 27].

At the level of T5, the TD deviates to the left before entering the superior mediastinum, at the posterior face of the esophagus. It ascends toward the left side of the esophagus and is crossed anteriorly by the aortic arch. It passes posterior to the origin of the left subclavian artery, in contact with the mediastinal left pleura. In the cervical region, the duct bends at the level of C7 and rises 3–4 cm above the clavicle [7, 10, 14, 27, 30, 31]. It then runs posterior to the left carotid sheath containing the common carotid artery, jugular vein, and vagus nerve [19]; it lies anterior to the subclavian artery and anterior to the vertebral vein at all times. The TD terminates at the junction between the left subclavian vein and left internal jugular vein in 38% of cases [21]. Nevertheless, many anatomical variations and alternative pathways have been reported [5, 9, 27].

Traumatic chylothorax is a rare complication following thoracic trauma or surgery (0.5–3% after esophageal surgery) yet serious, leading to 50% of mortality rate [28]. Therefore, any variations of the TD are of utmost importance to a thoracic surgeon because of its susceptibility to damage during surgical procedures [37]. Injuries to the TD can occur in complex pediatric surgeries involving the aerodigestive and vascular mediastinal structures, such as retroesophageal right subclavian artery surgery [11]. These injuries result in postoperative chylothorax and chylous fistula with significant pulmonary, infectious, and metabolic consequences [24]. Pediatric cardiac malformation surgery, scoliosis repair, and anterior spinal surgery are also important in this respect [10, 13, 25, 32]. In most cases, these lesions are reported at the cranial portion of the duct [13, 39].

Surgery should be considered when medical management of chylothorax has failed to reduce chyle flow [3, 26], with a wide range of successful rates between 67 and 100% [3, 6]. Among the various surgical methods for persistent chylothorax, TD ligation via right thoracotomy is regarded as the standard procedure for treatment of prolonged and massive chylous effusion [3]. Thoracoscopic right mass ligation has also been described as a minimally invasive procedure for the management of massive chylothorax [3].

Reports in the literature state that initially an attempt is made to selectively ligate the TD, which requires a TD dissection step to allow for better visualization of the duct. When the selective procedure cannot be performed, a mass ligation of all tissue between the aorta and azygos vein just above the diaphragmatic hiatus is undertaken [36], despite any anatomical variations. It is recommended to perform the ligature at the hiatus level, where the TD exhibits fewer anatomical variations [33], even though the incidence of multiple duct patterns at the diaphragmatic level is reported to be as high as 30% [31, 38]. Thus, there is a risk of not ligating or injuring poorly visualized multiple ducts during a selective ligation procedure. Therefore, it is necessary to find a site in which the TD is consistently located, in all its forms, for mass ligation. Although many studies have described the anatomy of the TD and its various anatomical variations, this is the first study to describe a site where it is constantly present, in its entirety and invariably despite its various anatomical variations, thanks to cadaveric dissections.

Therefore, the aim of our study was to analyze the anatomy of the TD to identify a site where the TD is systematically found, even in multiple duct patterns. This will help us determine the preferable level for mass ligation of the TD in the management of iatrogenic chylothorax, taking into account its numerous anatomical variations. To this end, we explored the pathway of the TD via an anatomical cadaveric study. We also aimed to confirm data from previous studies focused on the anatomical relationship between the TD and the vascular and aerodigestive mediastinal structures, thanks to our large database composed by 70 cadaveric dissections. Indeed, a better knowledge of the anatomical relationships of the TD help avoiding iatrogenic postoperative chylothorax in pediatric surgical procedures involving the aorta, supra-aortic trunk, or the esophagus, especially in aortic arch anomalies with vascular ring (AAvr) surgery.

Material and methods

Study design

Dissections of the TD were performed on 75 adult cadavers preserved in formalin solution (ARTHYL26®) at the LADAF (French Alps Laboratory of Anatomy), University of Grenoble Alpes Medical School, Grenoble, France from 2012 to 2018. Dissections were carried out respecting the French legislation for body donation. Body donation was based on free consent by the donors when they were alive. All dissections were done with the utmost respect for the deceased.

Throughout this observational study, the QUACS (Quality Appraisal for Cadaveric Studies) scale recommendations were followed [42] to appraise the methodological quality of the cadaveric studies.

Bodies with abdominal, cervical, or thoracic scars induced by surgery were not included in this study. During the dissection, bodies presenting abdominal, thoracic, or cervical neoplastic invasion were excluded. Data from bodies for which the TD could not be visualized were not analyzed. No distinctions were made regarding the cause of death. Before the dissection, cadavers were preserved in a cold room at 4 °C.

Each dissection was photographed with a Canon EOS 400D digital reflex camera (lens: 18–55 mm). The dissection photographs were then analyzed by the authors who did not participate in the dissection for verification purposes.

Dissection protocol

We established an optimized dissection protocol for the study of the TD. Bodies were placed in supine position, with the hands behind the head or along the trunk. For the dissection, a bilateral Cormier–Dartevelle–Grunenwald cervicothoracic approach was used in association with an anterolateral thoraco-abdominal wall excision.

Two incisions were performed medially to each sternocleidomastoid muscle, and converged at the superior part of the sternal manubrium. The vertical incision was prolonged until the 2nd intercostal space. A transversal incision joined the right and left posterior axillary lines with the initial vertical incision, at the level of the 2nd intercostal space. Two incisions were made, one on each side, along the posterior axillary line, from the 2nd intercostal space to the iliac crest. The skin and fat tissue were resected and the major pectoral muscle was cut at its manubrial insertion site. The internal jugular veins in their cervical portion and the left and right subclavian veins before their subclavicular path were individualized to clip them. The internal jugular vein, subclavian vein, and brachiocephalic venous trunk were clipped to avoid diffusion of the injection product beyond the termination of the TD.

The ribs were sectioned along the posterior axillary line and sternotomy was performed. The abdominal skin and muscles were folded to provide access to the thoracoabdominal viscera. The body was eviscerated, removing the liver, digestive tract, lungs, and heart.

The region between the abdominal aorta and the azygos vein was carefully explored, searching for the cisterna chyli, if present, or the initial portion of the TD.

Once the TD was identified, the injection product was prepared. It consisted of 5 mL water, 20 mL latex, and 10 mL methylene blue. At the beginning of the study, turpentine was used instead of latex for the injection solution (26% of the bodies). Latex solutions were used for the other bodies because they had less leakage and the injections were easier to perform.

The origin of the TD (convergence of the lymphatic trunks or cisterna chyli) was catheterized on the right side of the aorta and injected with 10 mL of solution. The clamped veins were checked to see whether the injection product had reached all the way to the end. The quantity injected varied according to the morphology of the duct. For bodies injected with latex, a 1-day latency period was required to allow for hardening before performing the TD dissection.

The dissection of the TD was then carried out from the injection site to its termination(s).

The Cormier–Dartevelle–Grunenwald approach allowed for better access of the TD termination, following the cervical trajectory of the duct and avoiding its injury.

Data collection

The origin of the TD was systematically explored, and the presence or absence of the cisterna chyli was recorded. We considered that a cisterna chyli was present when a bulging or TD dilatation compared with the rest of the duct was macroscopically discernable. Classification into type I, II or III was done according to the classification of Loukas et al (2007) [23]. The morphology of the TD was characterized as single, double, or plexiform. The ending of the TD was also explored; its multiplicity and ending site were recorded.

The location and anatomical relationships of the TD were studied in the postero-inferior mediastinum, at levels T3 and T4. The vertebral level of the median line crossing was noted. The location of the TD relative to the aorta, azygos vein, and esophagus in the postero-inferior mediastinum from level T5 to level T12 was recorded. At level T4, the anatomical relationships of the TD with the aortic arch and the ligamentum arteriosum as well as with the esophagus were studied. The location of the TD at the level of T3 was recorded relative to the left subclavian artery (SCA).

Statistical analysis

The characteristics of the study population are described using proportions for categorical variables, and means with standard deviations (SD) or medians with interquartile range (IQR) for continuous variables. The normality of the quantitative parameters was assessed via a graphical verification of the distribution symmetry. Qualitative variables are represented by counting and percentage [12].

The conditions of application of all the statistical tests used were checked.

All of the statistical analyses were carried out using the RStudio software (version 1.0.143-© 2009–2016 RStudio, Inc.).

Results

A total of 80 adult cadavers, 35 males and 45 females, were dissected. Five specimens were excluded because of the presence of a mediastinal neoplastic thoraco-abdominal invasion complicating the visualization of the TD. Five specimens were dissected but the injection did not allow the visualization of the TD (4 with turpentine protocol and 1 with latex protocol). Data from 70 specimens were analyzed. The characteristics of the population are described in Table 1.

Turpentine injection solution was used in the first 18 bodies (26%) and latex solution in the other 52 bodies (74%). On average, two injections were needed to visualize the vein spread.

Table 1 Baseline characteristics of the study population

Sample, *n*	75
Age, median ($IQR_{25–75}$)	86 (80–92) years
Sex, *n* (%)	
Male	33 (44%)
Female	42 (56%)
Height, average (SD)	161.2 (150.5–171.9) cm
Weight, median ($IQR_{25–75}$)	55 (45–65) kg

The cisterna chyli was present in 32 of the 70 cadavers (46%). In the other cases, the origin of the TD was single after the convergence of the lumbar trunks (44%) or plexiform (10%). The external morphology of the TD was single in 70% of the cases, double in 20% of the cases, and plexiform in 10% of the cases. The TD crossed the median line between vertebral levels T8 and T10 in 81% of the cases and between T5 and T7 in 19% of the cases.

In the postero-inferior mediastinum (levels T5–T12), the TD was systematically located between the left anterolateral border of the azygos vein and the right border of the descending aorta (Fig. 1). In cases where the external morphology of the TD was single ($n=49$), it was always situated between vertebral levels T9 and T11. When the TD external morphology was double or plexiform ($n=21$), it was always found between vertebral levels T8 and T10 (Table 2). In 21% of the cases, the TD crossed the azygos vein on its left anterolateral (left) border. From levels T5 to T12, the TD was posterior relative to the esophagus in 86% of the cases and located left posteriorly in 14% of the cases.

At the level of T4, the TD location was posteromedial in 27% of the cases relative to the aortic arch. In the other 73% of the cases, the TD had no direct relationship with the aortic arch. In 42% of the cases, the TD was posterior relative to the esophagus, and right–posterolateral in 27% of the cases, and left–posterolateral in 31% of the cases.

At the level of T3, the TD was anteromedial to the SCA in 21% of the cases, medial in 51%, and posterior in 28%. The TD had no anatomical relationship with the ligamentum arteriosum at the level of T3 in 100% of the cases. At T3, the TD was on the left border of the brachiocephalic venous trunk (BCVT) in 18% of the cases and posterior to it in 82% of the cases (Fig. 2).

Three different ending sites were found in this study. The TD ended in the left jugulo subclavian angle in 52% of the cases, left internal jugular vein in 28% of the cases, or left subclavian vein in 20% of the cases.

Fig. 1 Location of the TD in the postero-inferior mediastinum, dissection view 1, parietal pleura covering the dorsal vertebrae; 2, azygos vein; 3, TD (injected); 4, thoracic aorta; 5, esophagus

Discussion

Embryological origin of the anatomical variations

The complexity and variability of the TD originate from its embryogenesis. The lymphatic system begins forming during the 6 week of development. During organogenesis, the first lymphatics buds are located underneath the internal jugular veins at the origin of the neck. At the end of

Table 2 Location of the TD in the postero-inferior mediastinum (T12–T5) relative to the aorta, azygos vein, and esophagus

Aorta%	Azygos vein%	Esophagus%
Right (63)	Left (79)	Posterior (86)
Right anterior (37)	Left anterior (21)	Left posterior (14)

TD Thoracic duct

Fig. 2 Location of the TD in the upper mediastinum relative to the supra-aortic trunks, dissection view 1, TD (injected); 2, left SCA; 3, left common carotid artery; 4, brachiocephalic artery; 5, aortic cross; 6, left IJV; 7, left subclavian vein; 8, left brachiocephalic vein; 9, left venous angle

the embryonic period, there are six primary lymph sacs. Lymphatic vessels develop similar to venous ones and join the lymph sacs. The jugular lymph sacs then join the cisterna chyli in the form of a bilateral system of lymphatic trunks, connecting across the midline by numerous collateral anastomoses. From these, only the inferior portion of the right trunk and the superior portion of the left trunk, with a diagonal anastomosing channel at T4–T6 segments, are part of the definitive TD. Thus, the lymphatic system, initially bilateral and symmetrical, evolves towards an asymmetrical distribution. The rest of the ducts involves during the foetal development [14, 15]. The complexity of the embryological mechanisms of the lymphatic tracts explains the great anatomical variability of the definitive TD.

Origin and external morphology

Previous studies observed a cisterna chyli in 50% (of 22 bodies, on a cadaveric study [8]), 20% on a lymphographic study [43], and 44.4% (of 45 bodies, on a cadaveric study [4]). We observed a cisterna chyli in 46% of our dissections, consistent with the rates reported by Bapuji et al on their cadaveric dissection study on 45 bodies [4]. The cisterna chyli was found in 18 of the 39 female bodies (46%) and in 14 of the 31 male bodies (45%). These results are similar to those reported by Bapuji (2018), suggesting that the likelihood of a cisterna chyli being present is the same for both sexes. Loukas et al. (2007) observed a cisterna chyli in 83.3% of their dissections on 120 bodies [23]. The difference observed can be due to the use of different definitions of the cisterna chyli [23]. The lower rate of cisterna chyli visualized in Wirth study (20%) could be explained by the different methodology, using lymphography on alive humans [43]. In our study, we considered that the cisterna chyli was present when a bulging or TD dilatation compared with the rest of the duct was macroscopically discernable.

Jacobsson (1972) classified the origin of the TD into 3 types on a 122 bodies' cadaveric study. A single thoracic type arising from the confluence of the lumbar and intestinal trunks (Type I), the confluence of the two lumbar trunks (Type II), or from plexuses formed by the lumbar and intestinal trunks (Type III) [17]. Originally, Jacobsson's study (1972) found 20%, 55%, and 24% of Type I, II, and III forms, respectively. Srinivasarao et al. (2013) found similar results with 20%, 60%, and 20% of cases for Type I, II, and III, respectively [35], on a 45 cadaveric anatomical study. In our study, when the cisterna chyli was absent (54%), the origin of the TD appeared to be simple after convergence of the lumbar trunks in 44% of the cases, corresponding to Jacobsson's Type II form, or plexiform in 10% of the cases, corresponding to Type III. We did not find any Type I origin pattern.

The external morphology of the TD, after its origin, was classified as single when it did not have any duplication, double when there was a duplication before merging again, or plexiform when it gave off more than two branches before merging again. In 70% of the cases, the TD had a single form cranially to its origin. Bapuji et al. (2018) found a duplication in all of their cases, involving different vertebral levels [4]. Phang et al. (2014) reported multiple channels or duplications in 40% of cases, on different vertebral levels from T1 to T8 on their 532 bodies' cadaveric study [27]. We found multiple channels or duplication of the TD in 30% of our cases. At its thoracic segment, the TD had a duplication in 20% of the cases in our study, involving different vertebral levels from T2 to T12. A plexiform morphology was observed in 10% of our cases.

Bapuji et al. (2018) described the obliquity of the TD at the vertebral level where it crossed the midline [4]. They found that the TD crossed the midline between levels T3 and T7 in all of their cases, with varying vertebral levels. In 40% of the cases they found a crossing between levels T4 and T6, in 20% between T3 and T6, in 24.4% between T4 and T7, and in 15.5% between T3 and T7. Pulice et al. (2016) described the crossing of the midline at the level of T7 in all of their dissections ($n = 4$) [29].

Phang et al. (2014) [27] reported that in rare cases (in 1–6% of the cases) the duct did not cross to the left and remained on the right. Our results differ slightly from those of Bapuji (2018) [4], with the duct crossing the midline between level T8 and T10 in 81% of our cases and between T5 and T7 in 19%.

Thoracic duct pattern and implication for surgical treatment of chylothorax

Previous studies reported that the TD always passed through the aortic hiatus on the right of the aorta to enter the thorax [4, 27]. Anatomy textbooks and previous studies have also reported that as the TD traversed from the abdomen into the thorax, it ascended on the right side of the vertebral column on the anterior surface of the aorta and azygos vein [1, 4, 8, 17, 41]. Our results are in agreement with those of previous studies, as the TD was found consistently between the left anterolateral border of the azygos vein and the right border of the descending aorta in our series. When the external morphology of the TD was single ($n = 49$), it was always situated between vertebral levels T9 and T11; when the external morphology was double or plexiform ($n = 21$), it was always found between vertebral levels T8 and T10 (Table 2).

Therefore, our results suggest that there is a portion of the TD trajectory that can always be located, whether it's external morphology is single or multiple. Indeed, 100% of the TDs in our study ($n = 70$) were located between the left anterolateral border of the azygos vein and the right border of the ascendant aorta, between levels T9 and T11, in all types of external morphologies.

These results thus favor right mass ligation of the TD, between the right border of the descending aorta and the azygos vein, at the level of T9–T10, including the lymphatic structures and surrounding adipose tissue (Fig. 3, Fig. 4). Our results also show that the TD crossed the azygos vein on its left anterolateral border in 21% of the cases. In these cases, the azygos vein can be ligated with the TD if necessary during the mass ligation with minor or rare complications, such as postoperative congestion of the mediastinum and lung or pneumonitis [26, 40]. The procedure can be performed via a right thoracoscopic mass ligation, minimizing postoperative complications in comparison with a right thoracotomy approach [3, 26]. The procedure can be aided by enteral feeding of 50 mL cream before the surgery, enhancing the visualization of the TD [26]. The dissection and isolation of the TD for selective ligation thus being unnecessary, injuries to the non-damaged remnant TD and its neighboring structures can be avoided, as can the risk of not visualizing one of the collaterals or a duplication.

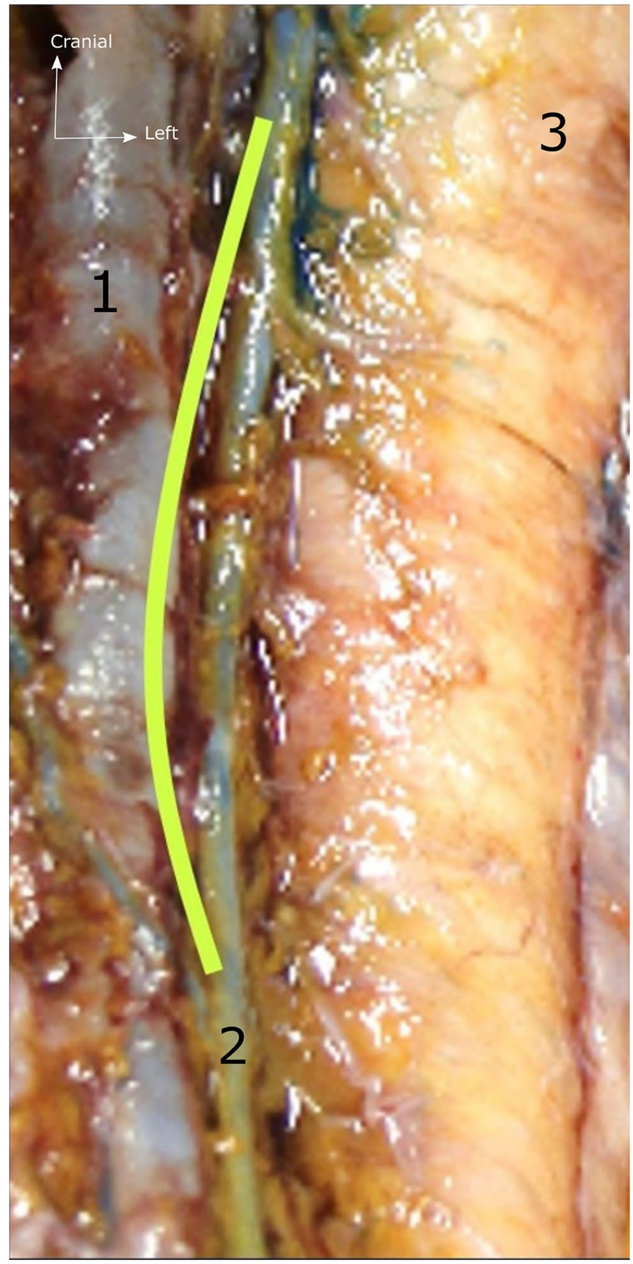

Fig. 3 Preferable site for mass ligation of the TD, dissection view. The mass ligation should include the TD and surrounding soft tissue between the right border of the aorta and the left anterior border of the azygos vein. The azygos vein can be included in the mass ligation. 1, azygos vein; 2, TD (injected); 3, thoracic aorta; line, mass ligation content (TD + surrounding soft tissue)

Iatrogenic chylothorax prevention in aortic arch anomalies with vascular ring (AAAvr) and ductus arteriosus surgery

In our study, at the level of T3, the TD was situated anteromedial of the left SCA in 21% of the cases, medially in 51%, and posteriorly in 28% of the cases. Previous studies and anatomy textbooks described the TD as running posterior to the initial segment of the left SCA, in close contact with the left mediastinal pleura, in Poirier's triangle, and delimited by the aortic arch, left SCA, and vertebral column [14, 20, 38]. The TD did not have a lateral pathway relative to the left SCA in our study, nor in any case reported in the literature.

The literature describes that the TD is crossed anteriorly by the aortic arch at level T4, on cadaveric studies and CT studies [14, 18, 20]. We found similar results, with the TD

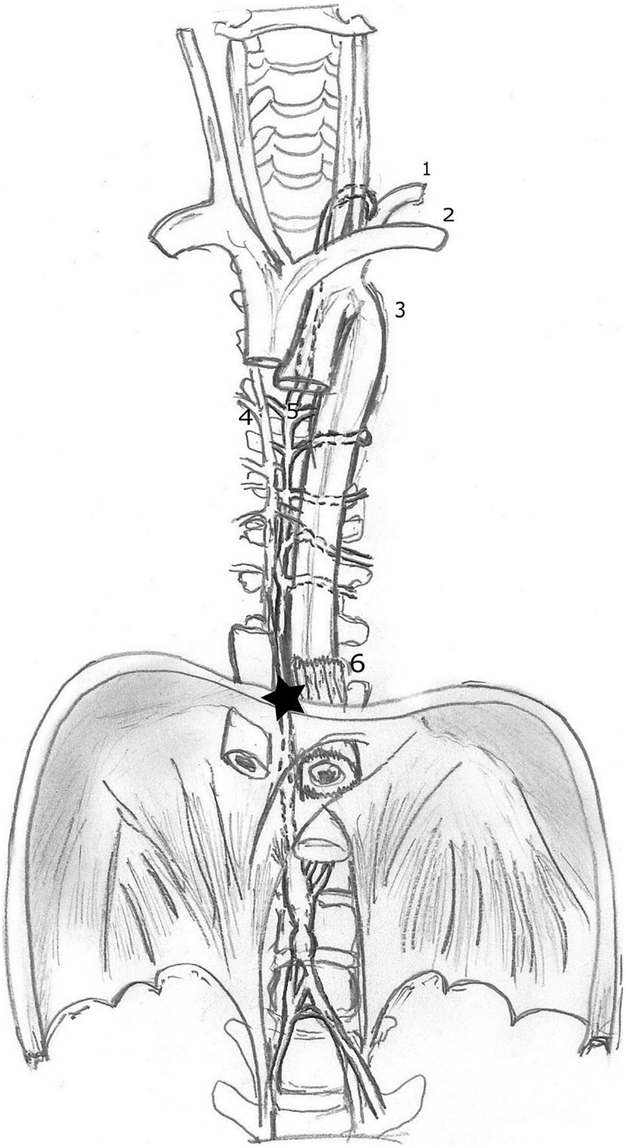

Fig. 4 Global view of the anatomy of the TD and the preferable vertebral level for TD mass ligation 1, left SCA; 2, left subclavian vein; 3, thoracic aorta; 4, azygos vein; 5,TD; 6, esophagus; star, preferable level for TD mass ligation (facing vertebral levels T9–T10), according to our findings

being situated posteromedial to the horizontal segment of the aortic arch in 27% of the cases, and not having a direct anatomical relationship with the latter in 73% of the cases. We did not find any anatomical relationship with the ligamentum arteriosum.

In our study, the TD was situated posterolateral to the esophagus at the level of T4 in 27% of the cases.

We therefore recommend an incision of the mediastinal pleura lateral to the left SCA during surgical procedures for AAAvr repair, when performing ligation/section of the circling vascular remnants via left thoracoscopy. The left SCA should then be followed in a caudal direction strictly at its lateral side as a guide before accessing the ending of the vascular remnants to be resected at level T4. In the case of a double aortic arch, the vascular remnant corresponds to the fourth and sixth embryological aortic arches. In the case of a right aortic–left ligamentum arch, the vascular remnant corresponds to the sixth aortic arch, according to the International Congenital Heart Surgery Nomenclature Database Committee [2]. These recommendations should help avoid injury of the TD during surgery for aortic arch anomalies and ductus arteriosus. Release of the tracheo-esophageal axis is recommended in circling AAAvr surgeries after the section of the non-dominant branch [16, 22, 34]. Our results suggest that such procedure should be avoided, because in 27% of the cases, the TD remains posterolateral to the esophagus. Indeed, if a lateral approach is to be practiced to avoid iatrogenic chylothorax during surgery for AAAvr, it should not be continued at the esophageal level at T4 because of the possible presence of the TD (in 27% of cases).

TD termination

The TD most commonly terminates in the internal jugular vein (IJV), the jugulovenous angle, and the subclavian vein [27]. In a 532 cases, literature review by Phang et al. (2014), the TD ended in the IJV in 46% of the cases, in the jugulovenous angle in 32% of the cases, and in the subclavian vein in 18% of the cases. Other terminations were found in 4% of the cases [27]. Bellier et al. (2019) described, in their literature review of 1352 cases, that the TD ended most frequently in the IJV (54% of the cases), followed by the jugulovenous angle in 26% of the cases, and in the subclavian vein in 8% of the cases. Other terminations were reported in 12% of the cases [5]. We found slightly different results, with a jugulovenous termination in 52% of the cases, an IJV termination in 28% of the cases, and a subclavian vein termination in 20% of the cases. These differences can be due to sampling fluctuations.

Study limits

Our study presented several limits. There were different investigators during the study, this may have cause interpretation bias attributable to the interobserver variability. This bias was limited by following the QUACS recommendation [42] when applicable, and all the dissections were supervised by the same two coordinators during the whole study. Second, we dissected 75 bodies, after excluding the 5 cases with thoracic condition, but the TD was not found in 5 bodies, possibly due to an inadequate injection material at the beginning of the study.

The presence of a cisterna chyli was assessed when a bulging or TD dilatation compared with the rest of the duct was macroscopically discernable. This difference of size compared with the TD was subjective and was not properly stated by a measured difference of size.

We encountered problems in the turpentine injection protocol at the beginning of the study because of the absence of adequate needles in accordance with the small size and the fragility of the TD within in the context of post-mortem tissues, which was overcome using a catheter for injection. The inadequate material was indeed leading to poorly injected TD which course was more difficult to follow compared with the well injected ones. This limitation was taken into account by not analyzing the data from these bodies.

Finally, another limitation was the population's median age, 86 years old and the predominance of formalin-fixed bodies; consequently, further studies assessing these findings on a pediatric population should be run.

Conclusion

This study confirms the important anatomical variations of the TD. Nevertheless, our results provide anatomically based evidence supporting an effective mass ligation of the TD at levels T9–T10, between the right border of the aorta and the left border of the azygos vein, eventually including the latter. Our study also offers valuable information on the anatomical relationships of the TD at level of T3 and T4, describing a safe path for AAAvr and ductus arteriosus surgery via left thoracoscopy to avoid TD lesions and postoperative complications. Our study also suggests that the release of the aerodigestive tract after resection of the vascular remnants in AAAvr surgery should be avoided so as to prevent TD lesions. Studies assessing the non-variability of the anatomical relationships regarding the vertebral levels between adults and children would be valuable to confirm the present study findings on pediatric population.

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Author contributions PYR: protocol/project development, critical revision of the manuscript. ESC: acquisition of data, data analysis/interpretation, manuscript writing. NEH: acquisition of data, drafting of the manuscript. AEH: acquisition of data, drafting of the manuscript. AB: data analysis, critical revision of the manuscript. PLV: data analysis, critical revision of the manuscript. JC: acquisition of data, data analysis/interpretation. CQ: acquisition of data, data analysis/interpretation. RF: data analysis, critical revision of the manuscript. PC: protocol/project development, manuscript editing. CP: protocol/project development, critical revision of the manuscript. YR: protocol/project development, manuscript drafting.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this article.

Ethical approval The French Alps Laboratory of anatomy uses bodies issued from donation, respecting the French funerary legislation.

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