Pediatric Thoracic Surgery

Girolamo Mattioli
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Michele Torre
Editors

Springer

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Editors
Girolamo Mattioli
Department of Pediatric Surgery
IRCCS Giannina Gaslini Institute
Genova
Italy

Michele Torre
Unit of Pediatric Thoracic
and Airway Surgery
IRCCS Istituto Giannina Gaslin
Genova
Italy

Paolo Petralia
IRCCS Istituto Giannina Gaslini
Genova
Italy

ISBN 978-3-030-74667-4 ISBN 978-3-030-74668-1 (eBook)
https://doi.org/10.1007/978-3-030-74668-1

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Pediatric thoracic surgery is an exciting field of pediatric surgery, requiring a number of conditions to get the best results: multidisciplinary approach, use of modern technological tools, and a surgical training based on solid anatomical, and physiopathological knowledge combined with a vast experience of case management. This latter point is not easy to be achieved, due to the relative paucity of cases in many pediatric hospitals.

For this reason, pediatric thoracic procedures are often performed by adult thoracic surgeons and not by pediatric surgeons. This book describes in a simple and direct way the most frequent congenital and acquired pediatric thoracic anomalies and illustrates the multidisciplinary experience of a group of professionals working in a large national referral pediatric Institution. We are convinced that the pediatric specificity is a value to be preserved and defended, especially in thoracic surgery, where the concept of anatomical and functional reconstruction and restitution to physiological conditions represents one of the key points to plan the surgical approach, which must take into account the physical, functional, and psychological development of the patients. The book is directed to medical students, trainees in pediatric surgery, young pediatric surgeons who want to explore one of the most challenging and exciting fields of pediatric surgery.

Genova, Italy — Girolamo Mattioli
Genova, Italy — Paolo Petralia
Genova, Italy — Michele Torre

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Part I

Introductory Aspects

1 Thoracic Surgery in Pediatric Patients

Girolamo Mattioli and Federico Palo

Minimally invasive surgery techniques, since their introduction in the mid-70s, have been increasingly performed in children, thanks to the less invasiveness and faster recovery, and today, thanks to technological development, their use has also been extended to newborns and infants [1–3]. In particular, the benefits of thoracoscopic surgery (TS) include less postoperative pain, shorter hospital stay, fewer wound complications, less long-term musculoskeletal sequelae, and better aesthetic outcomes [4, 5].

In the last 15 years, thanks to the widespread use of minimally invasive surgery, especially for abdominal procedures, the number of thoracoscopic procedures performed is increased, and more and more pediatric surgeons are adopting this technique not only for diagnostic evaluation but also for the operative. Notably, TS requires a significant learning curve, and it is still uncertain which types of thoracoscopic procedures should be recommended as a gold standard.

TS conveys with it several concerns, such as anesthetic considerations, adequate workspace, and control of vascular structures. Advances in new-generation instruments including high-resolution cameras, shorter 3-mm instruments, 5-mm endo-clip, upgraded linear staplers, new energy sources such as harmonic scalpel technology or radiofrequency vessel sealer, and current techniques for single-lung anesthesia have further popularized TS in children. Furthermore, TS is optimized by single-lung ventilation that can usually be accomplished without bronchial blockage with insufflation of CO_2 into the affected pleural cavity with a pressure of 4–8 mm Hg. If one-lung ventilation is required, this can be obtained by placement of numerous devices such as double-lumen endotracheal tube or a single-lumen endobronchial tube [6]. Complications during pediatric minimally invasive thoracic procedures are seldom reported in the literature [7].

Recently, robotic surgical technology began to have a very important role in pediatric surgery. Characteristics of robotic surgical platforms include motion scaling, greater optical magnification, enriched vision, increased instrument dexterity, tremor filtration, and exclusion of the fulcrum effect. These enhancements seem to further ameliorate conventional minimal access surgery [8–10]. Thus, robot-assisted surgery could overcome limitations associated with contemporary surgical technology in pediatric surgery and offer the opportunity to include more complex procedures in children.

G. Mattioli (✉) · F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini,
University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_1

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2 Management Aspects: Quality, Ethics, and Economic Sustainability

Paolo Petralia and Ubaldo Rosati

2.1 Ethical Aspects

The introduction of new surgical techniques in a complex field such as surgery brings with it several ethical aspects to consider.

When the chances of therapeutic choices increase in such a vast field as that of surgery with a spectrum of interventions that can range from very invasive procedures to less invasive procedures, such as laparoscopy, thoracoscopy, up to endoscopic procedures, the main problem to ask is which technique is more ethically correct to offer to the patient. The main problem is related to the possible conflict of interests that could arise, because nowadays, the patient is more and more attracted by the possibility to undergo surgery with minimally invasive technique, exclusively evaluating only those that are the benefits and underestimating the risks, the concept of mini-invasiveness often being confused with the complexity of the intervention. This leads to generating one hazardous situation in which the main aspects, the indication and the outcomes of the intervention, are placed in the background.

In this regard, Jonsen et al. [1] and others have developed a model that allows the surgeon to assess both the clinical aspects and to develop a higher awareness of aspects of the patient's life and treatment. The model takes into consideration four aspects: the first concerns medical indications and objectives such as the possibility of surgery success and possible alternatives; the second aspect concerns the patient's preferences based on a risk–benefit ratio; the third concerns quality of life of the patient at the time of surgery, considering the current lifestyle and the expected time of functional recovery; and finally, the last aspect takes into account the presence of any conflicts of interest that may affect the choice of treatment. The application of this model allows the surgeon to have greater adherence to those that are ethical standards.

2.2 Economical Aspects

In parallel with the ethical aspects, it is necessary to consider the economic aspects that are required in order to guarantee the patient the best health outcomes.

It is not easy to deal with the economic issue when it comes to health.

P. Petralia (✉) · U. Rosati
IRCCS Giannina Gaslini, Genoa, Italy
e-mail: paolopetralia@gaslini.org;
ubaldorosati@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_2

Adapting the basic principles of the general economy to medicine, without going into the complexity of the health sector, inevitably leads to errors of assessment.

Although the health system is part of an economic system, it deserves special considerations. Resources and limits are two aspects that have to be taken into consideration when evaluating the actions to be undertaken. However, when these are applied, according to the common general economic theories, to a health model, what is obtained is often counterproductive and uneconomical.

When resources are scarce, priorities must be determined. To decide patient priorities is the core of the ethical issue in medicine.

Similarly, the economy aims to limit expenses and possibly earn money. In the medical field, setting limits could have a counterproductive effect, slowing down progress and preventing improvement.

Although economic aspects cannot be neglected, in the medical field, they should be considered with a different perspective that could be summarized with the expression "doing the right thing," where it is right in relation to the ethics of science and the economy.

2.3 Why Are Quality Standards So Important?

This is one of the main questions that every health care professional should ask himself every time he offers a service.

The standards help health systems to develop and evaluate very important issues, such as management, leadership, prevention and control of infections, and management of medical therapy, all of which influence the quality of services that the end-user receives.

Adherence to standards allows creating a solid health system, on which the public, those who provide services, and those in charge of their organization can rely, ensuring a high quality of services.

2.4 What Must Those Who Are Responsible for Maintaining These Quality Standards Evaluate and What Action Must be Taken to Guarantee Services Up to the Required Standards?

The first step is to evaluate these services and identify improvement actions to guarantee the required quality.

Afterward, one has to determine what type of assistance should be offered and identify the gaps in the current system.

The best strategic actions to ensure reliable and superior quality health services for the public are then identified. The focus is directed to promote all those activities that make the system efficient, knowing exactly the level of quality required from each one involved in the process and offering all the tools to implement these goals.

Constant feedback on what is the current level of quality is mandatory to detect gaps early.

Similarly, one has to verify that the services offered by the health system are standardized, which means they are verified, safe, and reliable. The human aspect is nonetheless important. All this work should be perceived by the service user, with the certainty that health care organizations are actively working to improve care.

Health standards are also useful as a comparison system between different health systems, allowing comparison on different levels. This helps governments, as they provide the best available evidence of the level of quality reached, playing, in this way, a key role in the decision-making process.

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Part II

General Aspects

3 Prenatal Diagnosis and Perinatal Management of Thoracic Anomalies

Dario Paladini

3.1 Normal Sonographic Anatomy of the Thorax

The thorax has a conotruncal shape. Its borders are represented cranially by the clavicles and the neck, caudally by the diaphragm, and laterally by the ribcage and the sternum. Posteriorly, the shoulder blades can be seen in a strict relationship with the ribs and the clavicles. In the thorax, the following regions/organs can be identified: the *lungs*, the *heart*, and the *mediastinum*, with the great vessels and the thymus, larger in the fetus than in the neonate.

Timing of examination. Ultrasound (US) assessment of the thorax can be carried out easily until 25–26 weeks of gestation. After this period, the increased mineralization of the ribs leads to significant acoustic shadowing, which limits the display of intrathoracic organs, especially if coronal or sagittal views are sought (see below). Besides, it must be emphasized that a good number of thoracic anomalies show temporal modifications through gestation; that is, they can appear only in the third trimester or even at birth (eg, diaphragmatic hernia), or, on the contrary, they can regress before birth as for congenital cystic adenomatoid malformations of the lung (C-CAML). Therefore, if an initial assessment of the thorax and the heart can be performed as early as 12–14 weeks of gestation, it should be noted that in order to follow-up abnormal cases, late third-trimester scans may be needed.

US approach and scanning planes (views). The regular shape of the thorax lends itself easily to a standardized US approach. However, it should be noted that the key view for the assessment of intrathoracic anatomy is the classic *four-chamber view* of the fetal heart. In fact, in this plane, most thoracic viscera can be displayed, including the ribs, the sternum, and the cutaneous outline. This is why most scientific societies consider the four-chamber view as the reference view to screen for intrathoracic and cardiac abnormalities. However, if the results from this view are abnormal, and a thoracic lesion is found, this should be explored further using coronal and sagittal views as reported below. The *midsagittal* and *parasagittal views* allow the display of the diaphragm as a hypoechoic layer below the basal aspects of the lungs and the heart and above the liver and the stomach. The diaphragm shows a curved outline, convex toward the thorax. It should be underlined here that the anomaly scan—which is the scan focusing on detecting most fetal congenital anomalies—is usually carried out in most countries at 18–22 weeks of gestation (in Italy at 19–22 gestational weeks).

Axial four-chamber view (Fig. 3.1). As already mentioned, this represents the fundamental plane where heart and lung anatomy are assessed. On

D. Paladini (✉)
Fetal Medicine and Surgery Unit, IRCCS Istituto Giannina Gaslini, Genoa, Italy
e-mail: dariopaladini@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_3

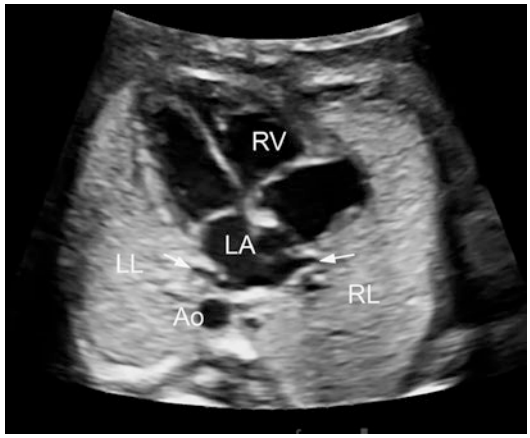

Fig. 3.1 Axial view of the thorax: Four-chamber view. In this view, the two lung fields (*LL* left lung, *RL* right lung), the heart (*LA* left atrium, *RV* right ventricle), and the descending thoracic aorta (*Ao*) behind the left atrium are visible. Laterally, two complete ribs are evident; posteriorly, one thoracic vertebra can be seen. The cutaneous outline, outside the ribcage, is also evident. Note that the right lung appears larger than the left lung

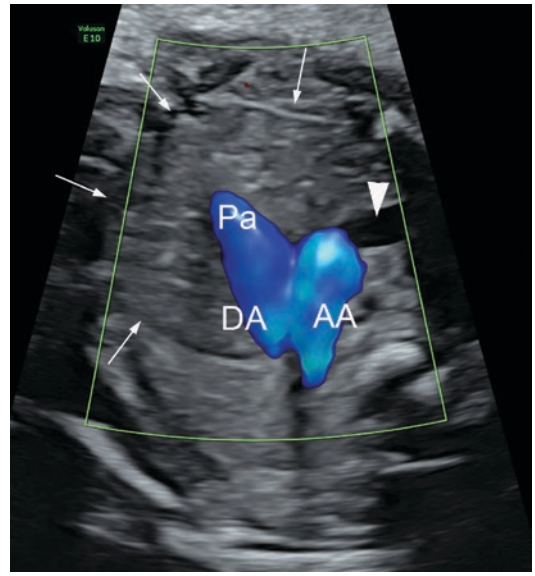

Fig. 3.2 Axial view of the upper mediastinum at 28 gestational weeks. The thymus (arrows), which is weakly hypoechoic in comparison with the lungs, can be seen anterior to the great vessels. (*AA* aortic arch, arrowhead: superior vena cava; *DA* ductal arch, *Pa* Main Pulmonary Artery)

this view, the following structures can and should be checked in addition to the cardiac anatomy which is not within the scope of this chapter: the thoracic outline, consisting of the two displayed ribs and the overlying soft tissues and skin; the two lungs, shown in cross-section; the thoracic aorta, lying in the prevertebral area just left of the midline and behind the left atrium (if the situs is *solitus*); and one thoracic vertebra, on the midline, posteriorly. Since the heart is mainly located in the left hemithorax, the right lung will appear larger than the left one (Fig. 3.1). In the normal fetus, the pleural cavity is virtual and does not show up; on the contrary, a thin film of fluid is often seen within the pericardium and should be considered a normal finding.

Axial view of the mediastinum (three-vessel view) (Fig. 3.2). This plane is parallel and cranial to the four-chamber view. It is routinely sought in fetal echocardiography in order to demonstrate the aortic and pulmonary arches and to detect aortic arch branching abnormalities. Its importance in the assessment of extra-cardiac anatomy lies in the fact that it allows one to visualize the thymus and study its relationship with the great vessels. The thymus, which is easier to recognize from the late second trimester onward, when it starts to undergo significant hypertrophy, appears as a well-defined roundish solid structure interposed between the great vessels, in the prevertebral region, and the sternum. It is weakly hypoechoic in comparison with the surrounding lungs (Fig. 3.2). Recently, another technique has been proposed to identify the thymic area, especially at earlier gestational ages, the so-called *thy-box*. This expression [1] is based on the fact that the thymus is bordered laterally by the two internal mammary arteries; hence, by tracing these two arteries with power Doppler or low PRF color Doppler, the thymic area can be easily identified on an axial view of the upper mediastinum. Behind the thymus and in front of the vertebra, the great vessels, the trachea, and, with some difficulty, the esophagus can be seen.

The esophagus (Fig. 3.3). The esophagus presents three portions: cervical, thoracic, and abdominal. The cervical portion is often visible behind the trachea, just below the vocal cords (Fig. 3.3a). The thoracic tract may be visualized in a near-midsagittal plane with the abdominal

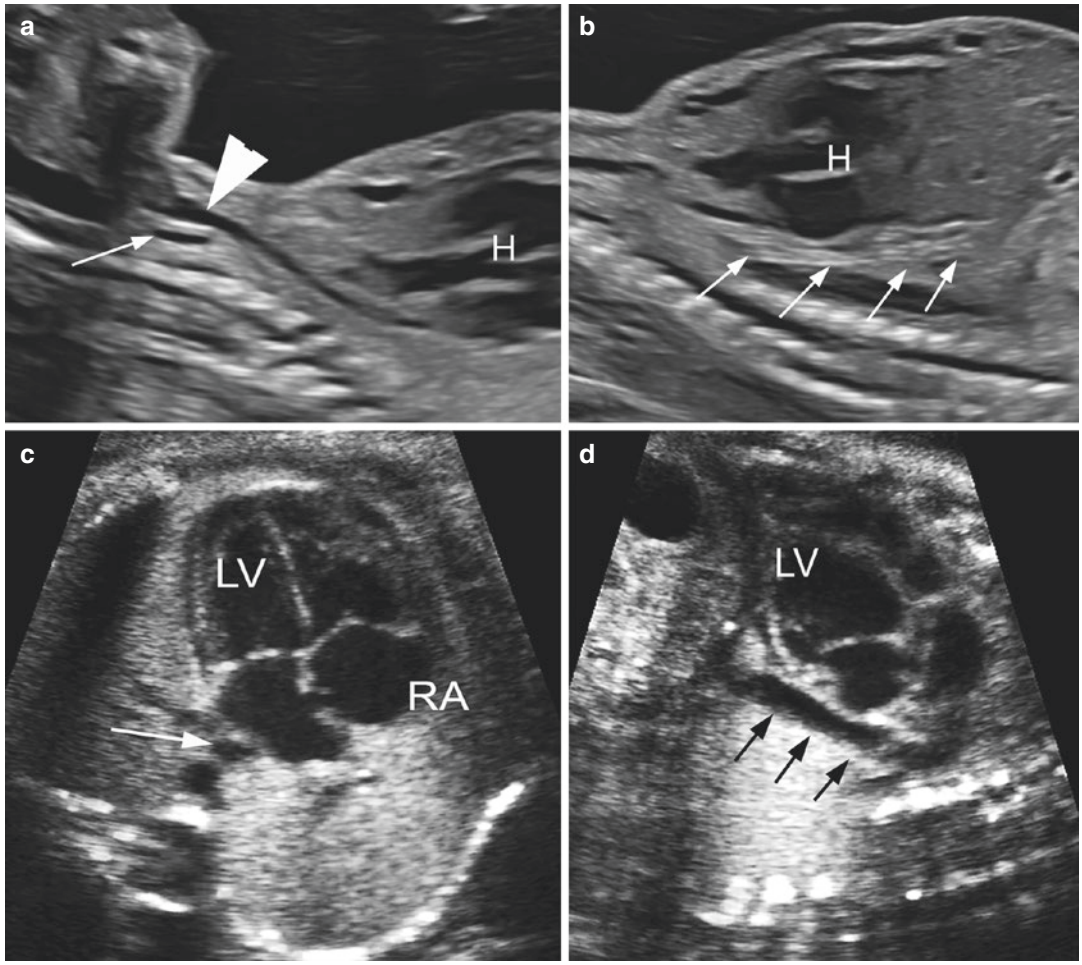

Fig. 3.3 Ultrasound views of esophagus. (**a**) Sagittal view of the fetal neck, thorax, and upper abdomen, showing the proximal part of the esophagus (arrow), behind the trachea (arrowhead); (**b**) The parasagittal view of the thorax demonstrates the thoracoabdominal course of the empty esophagus, described as 3–4 hyperechoic parallel lines (arrows); (**c**) On some occasion, when the fetus swallows a bolus of amniotic fluid, the esophagus remains distended for a few seconds and is visible behind the left atrium (arrow); in this case, it is necessary to differentiate the temporary dilation of the esophagus from an abnormal venous return (systemic or pulmonary). If the anechoic area is due to esophageal dilation, it disappears after a few minutes; in addition, the use of color or power Doppler may easily confirm or rule out a cardiovascular anomaly; (**d**) in the same fetus, the distended esophagus (arrows) can also be visualized on a longitudinal parasagittal plane of thorax and abdomen (*H* heart, *LV* left ventricle, *RA* right atrium)

portion deviated to the left. Some authors [2] have described the sonographic aspect of this organ, when empty, as a tubular structure composed of four parallel echogenic lines corresponding to the apposition of the anterior and posterior walls of the esophagus (Fig. 3.3b). After fetal swallowing, the esophagus fills with amniotic fluid, and it can appear as an anechoic structure (Fig. 3.3c, d). The thoracic tract may resemble a vessel. Power or color Doppler may be used to exclude its vascular origin. Also on the four-chamber view, the cross-sectional appearance of the esophagus distended by some amniotic fluid may be mistaken for that of an abnormal vessel as in abnormal pulmonary or systemic (azygos continuation) venous return. This artifact is shown in Fig. 3.3c.

Right parasagittal view. On the right parasagittal view, the whole of the right lung comes into view. The heart is not visible, being in the left

hemithorax. In this view, the diaphragmatic hypoechoic layer can be seen below the right lung. Care should be taken to consider the identification of the diaphragmatic plane in this view as a demonstration of an intact diaphragm: if the hernia is located on the other side, as in the Bochdalek type (see below), the contour of the right hemidiaphragm is normal. Also, it is important to note that this view can be employed advantageously to disclose the severe thoracic hypoplasia typical of lethal skeletal dysplasia.

3.2 Congenital Diaphragmatic Hernia (CDH)

Definition. The term *congenital diaphragmatic hernia (CDH)* encompasses a range of closure defects of the diaphragm. Because the intra-abdominal pressure is higher than the intrathoracic pressure, in the presence of a diaphragmatic defect, the abdominal viscera located near the defect migrate into the thorax. CDHs are classified according to the site of the defect: 75–85% of cases involve the left posterolateral area (*Bochdalek type;* Fig. 3.4); 10–15% of cases involve the right hemidiaphragm; and 3–4% of cases are bilateral hernias.

Etiology and pathogenesis. Embryologically, CDHs originate if normal closure of primary pleuroperitoneal channels does not occur. At 12 weeks of gestation, when the physiologic umbilical hernia disappears, the intra-abdominal pressure increases and may force the abdominal viscera through the hernia, if this is present. From a prognostic standpoint, the main problem of a CDH is not the defect itself but rather the occurrence and degree of pulmonary damage. This consists of severe alveolar hypoplasia induced by the long-term compression of the lungs exerted by the migrated abdominal viscera. After birth, the onset of pulmonary hypertension can further complicate the situation. The association of pulmonary hypoplasia with pulmonary hypertension represents the main determinant of death in neonates with nonsyndromic CDH [3].

Ultrasound diagnosis. The US diagnosis of CDH is, in most instances, indirect: What is detected is the abnormal intrathoracic position of the stomach and/or the other migrated viscera and the displacement of the heart and the mediastinum. These findings indirectly demonstrate the existence of the diaphragmatic defect. The intrathoracic migration of the abdominal viscera is recognized on the *four-chamber view*.

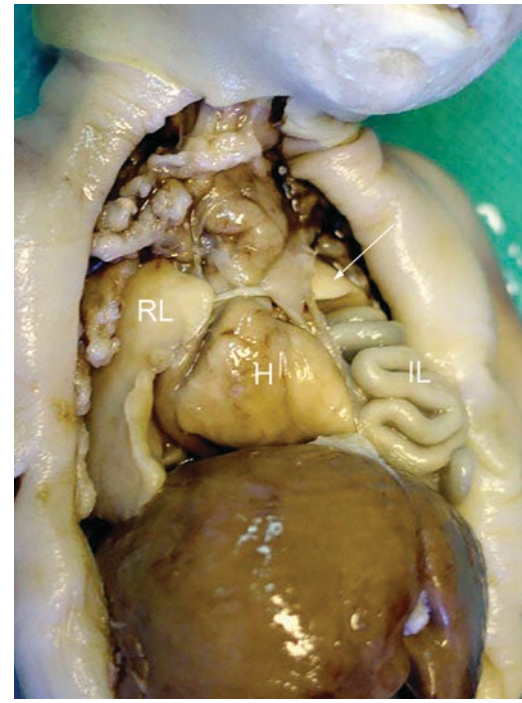

Fig. 3.4 Congenital diaphragmatic hernia, Bochdalek type (left, posterior). This specimen (22 weeks of gestation) shows herniation into the left hemithorax of ileal loops (IL), which hide the stomach. The heart (H) is displaced into the right hemithorax, where it compresses the right lung (RL). The liver is visible below. The arrow points to the hypoplastic left lung

Left posterolateral CDH. On the four-chamber view, the stomach is found either in the left hemithorax or in the mediastinal area (Fig. 3.5). In most instances, a few ileal loops can be found near the stomach, while the heart and the mediastinum are displaced contralaterally. Much more rarely, the spleen and/or the left liver lobe may migrate as well (Fig. 3.6a). In left-sided hernias, the stomach is found in the thorax in most cases (about 90%). In a minority of cases, only some ileal loops and/or the left hepatic lobe—but not the stomach—migrate into the thorax (Fig. 3.6b). If this is the case, only the dextrocardia and the

unusual inhomogeneous appearance of the left hemithorax may lead to the diagnosis. It should be emphasized that although the diaphragmatic defect occurs at 12 weeks of gestation, the moment at which the viscera herniate is extremely variable and ranges from the early second trimester to the first hours of life; in the latter instance, it is the first breaths that determine the migration of the viscera. Hence, CDH can be considered an "evolving" lesion, a concept that has obvious and deep medicolegal implications. This process is responsible for the fact that only 50–60% of CDHs are diagnosed prenatally [4]. The *longitudinal views (ventral approach)* allow one to detect additional signs that may confirm the existence of the hernia: a tortuous aspect of the inferior vena cava and the absence of the hypoechoic contour of the diaphragm (Fig. 3.7).

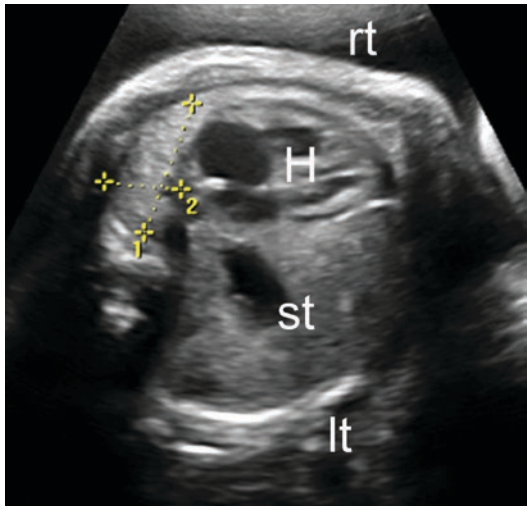

Fig. 3.5 Congenital diaphragmatic hernia, Bochdalek type. In this variant of CDH, the stomach (st) is visible in the middle of the thorax, or in the left hemithorax, while the mediastinum, with the heart (H), is shifted contralaterally. The measurements in yellow represent the two orthogonal diameters of the right lung, measures needed to calculate the Observed/Expected Lung-To-Head Ratio (see text) (*lt* left side, *rt* right side)

Right-sided CDH. These represent about 10% of all CDHs at birth. In the case of right-sided hernia, the US diagnosis is more challenging because the main finding leading to the final diagnosis of CDH in most instances, the intrathoracic displacement of the stomach, is absent, being the defect on the other side of the diaphragm. Nonetheless, there are some features that allow one to recognize a right-sided hernia in utero. The first is represented by an extreme leftward rotation of the heart, with a consequent abnormal increase in the cardiac axis: the heart appears squeezed toward the lateral wall of the thorax (Fig. 3.8). The second hint for diagnosis of

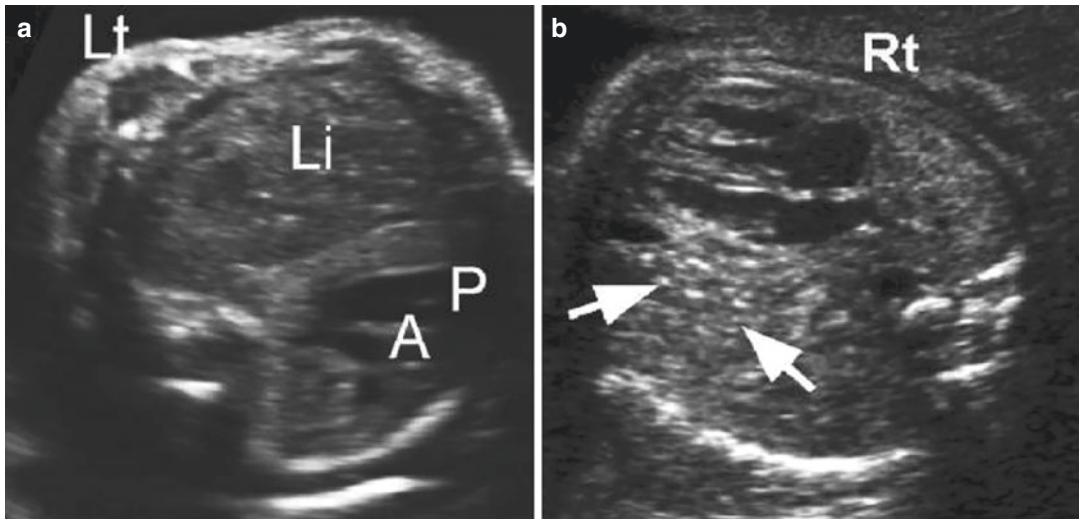

Fig. 3.6 Congenital diaphragmatic hernia, Bochdalek type. (**a**) In rarer cases, other than the stomach, the spleen, ileal loops, and/or the left hepatic lobe (Li) can also migrate into the thorax. (**b**) In the fetus, it is unusual but not impossible that a CDH is recognised only because of ileal loops (arrows) in the thorax associated with dextrocardia; (*A* aortic arch, *Lt* left side, *Rt* right).

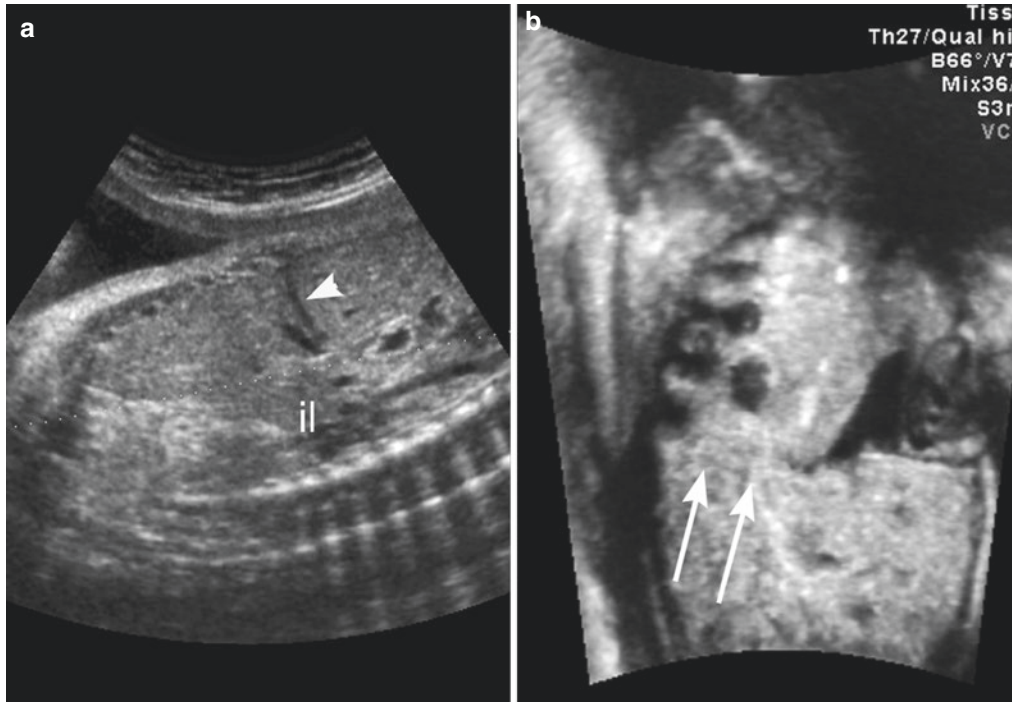

Fig. 3.7 Congenital diaphragmatic hernia, Bochdalek type. (**a**) The right parasagittal thoracic view can sometimes contribute to direct detection of the defect in the diaphragm, showing the interruption of the hypoechoic line of the diaphragm (arrowhead) and the presence of ileal loops (il) passing across the diaphragmatic line. However, this sign should not be considered as a primary finding; the most important clues to the diagnosis of CDH are the intrathoracic location of abdominal viscera and dextrocardia; (**b**) three-dimensional reconstruction of the coronal plane may help also to support the diagnosis, on some occasions. In this case, the same as panel (**a**), the same finding is shown on this plane, with the heart displaced in the right hemithorax and the loss of the hypoechoic line of the diaphragm on the left (arrows)

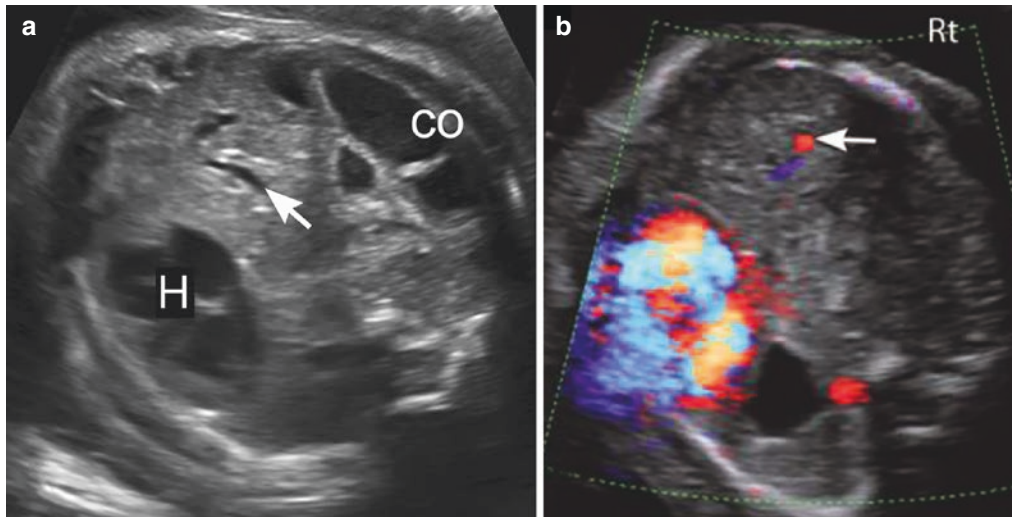

Fig. 3.8 Congenital diaphragmatic hernia, right-sided (third trimester). In 10% of cases, the diaphragmatic defect involves the right hemidiaphragm. In this case, the right hepatic lobe (and sometimes the gallbladder, as well) may migrate into the thorax. (**a**) On gray-scale ultrasound, the evidence of the hepatic flexure of the colon (co) in the thorax may contribute to the diagnosis as well as the recognition of suprahepatic veins (arrow); (**b**) color or power Doppler may be used to confirm the presence of the suprahepatic veins (arrow) in the thorax

a right CDH is the upward displacement of the right hepatic lobe: This is pushed upward by the absence of the counterpressure represented by the diaphragm and can be detected in the right hemithorax (Fig. 3.8). However, the latter finding is sometimes difficult to identify because the echogenicity of the lung and the liver are quite similar. High-frequency transducers and the use of power or color Doppler to identify the suprahepatic veins "in the thorax"—once suspicion of right CDH has been raised—help identify the intrathoracic position of the right hepatic lobe (Fig. 3.8b).

Three-dimensional US. The assessment of the thorax and, in particular, of the lungs may benefit from a 3D US approach. In particular, the diaphragmatic defect itself can be effectively studied both with surface-renderings of the reconstructed coronal view and with tomographic ultrasound imaging (TUI). The latter imaging modality allows one to display on a single panel a variable number of reconstructed two-dimensional (2D) sections as in computed tomography (CT) or MRI scan. Using this approach, the reconstructed coronal plane is used to display the extent and the site of the diaphragmatic defect (Fig. 3.7b).

Differential diagnosis. For left-sided CDH, the differential diagnosis includes the macrocystic subtype of ACML because the stomach might, at least theoretically, resemble the dominant cyst in a macrocystic CAM. Right-sided CDH should be differentiated from the solid, microcystic variant of CAML and pulmonary sequestration: The echogenicity of the intra-thoracic liver/intestine should be differentiated from the highly hyperechoic CAML, although the difference in "brightness" is usually significant.

Prognostic indicators. The most important prognostic factor for fetuses with CDH is the possible association with chromosomal anomalies and/or syndromes. In the case of isolated CDH, several US features have been assessed over the years for their capacity to predict the neonatal occurrence of lethal pulmonary hypoplasia and pulmonary hypertension: early gestational age at diagnosis, presence of a mediastinal shift, higher pulmonary artery resistance at Pulsed Wave Doppler [5], intrathoracic position of the liver (*liver up*), lung-to-head ratio (LHR) [6–9], and observed/expected LHR (o/e LHR) [10]. Of these, only the last three have proved acceptably reproducible and of sufficient although not exceptional prognostic value. However, in a logistic regression analysis, the *liver up* position apparently loses its independent prognostic significance when compared to the o/e LHR [10]. As for the LHR, this can be calculated by multiplying the two orthogonal diameters of the right lung, which is located between the ribcage and the heart in the right hemithorax (Fig. 3.9) and dividing the result by the head circumference. The measurements can be done in three ways: (1) measuring the longest lung diameter and the longest perpendicular diameter; (2) measuring the anteroposterior diameter of the lung at the midclavicular line by the perpendicular diameter at the midpoint of the anteroposterior diameter; and (3) tracing manually the limits of the lungs. The last method has shown the highest reproducibility [11] also because it can be more easily used in cases in which it is difficult to measure the lung. Currently, the procedure

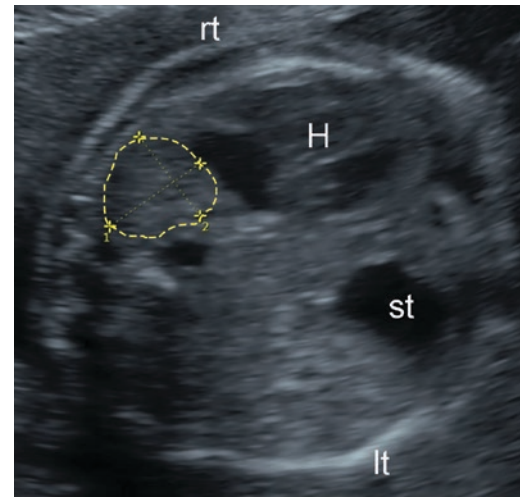

Fig. 3.9 Calculation of the lung-to-head ratio (LHR). This is performed by multiplying the two orthogonal diameters (yellow lines 1 and 2) or the tracing of the area (dotted line) of the right lung, which is located behind the heart, in a left-sided hernia. This value is then divided by the head circumference (CC) (see text)

of choice to predict the risk of death from pulmonary hypoplasia/hypertension in fetuses with isolated CDH is as follows [12]:

1. Select the axial four-chamber view of the fetal thorax, taking care in displaying the right side of the fetus closer to the transducer, for better measurements, and avoiding shadowing from the ribs.
2. Magnify the image so that the axial view of the thorax occupies the whole screen.
3. Select the method of choice for measurement of the lung, taking into consideration that the manual tracing has shown the highest reproducibility [12].
4. Divide the area of the lung (in squared millimeters) by the head circumference (in millimeters) to obtain the LHR. Care should be taken not to include the myocardium in the measurement.
5. Then, the *observed* LHR should be divided by the *expected* LHR to derive the o/e LHR [12].

Association with other malformations. In addition to the cases associated with syndromes, CDH can be associated with congenital heart disease and gastrointestinal and central nervous system anomalies. Another prognostic indicator has recently been reported in the literature and has still to be validated by other researchers: It seems that fetuses with CDH and a formerly increased nuchal translucency (NT) have a poorer outcome than those with a normal NT [13]. In particular, in this retrospective series of 80 cases with CDH and NT measurement 7/9 (78%), fetuses with CDH + NT > 95° died in the neonatal period versus only 24/62 (35%) of those with CDH and a normal NT.

Risk of chromosomal anomalies. This risk is relatively high (5–15%). CDH is mainly associated with trisomies 21 and 18 [14–16].

Risk of nonchromosomal syndromes. This risk is high (25–30%). A summary of the most important monogenic conditions that may present with CDH is shown in Table 3.1 [14, 15].

Prenatal management. Should CDH be diagnosed in a fetus, karyotyping *and* CGH-array are mandatory because of the relatively high risk of aneuploidy. In addition, a thorough anatomic scan should be performed by an expert in order to detect major and/or minor signs possibly leading to the diagnosis of one of the several syndromes associated with CDH (Table 3.1).

Fetal Surgery. The ability to prenatally identify a future nonsurvivor prompts the question for an intervention that can avoid that outcome. As CDH is a developmental problem, the ideal therapeutic window of opportunity logically is the prenatal period. Historically, this was first done by in utero anatomical repair (reviewed in [17]). Today, the only clinically applied intervention is fetal endoluminal tracheal occlusion (FETO) [18]. Tracheal occlusion prevents egress of lung liquid, which in turn causes increased pulmonary stretch, hence accelerated lung growth as evidenced by several animal experiments. Since its initial clinical introduction, FETO has evolved to a percutaneous procedure under local anesthesia, with fetal pain relief and immobilization. Also, several purpose-designed fetoscopic instruments were developed. The current diameter used is 10 F (3.3 mm), which is comparable to what is used for laser coagulation for a twin to twin transfusion syndrome. Essentially, it consists of a semi-flexible miniature fetoscope and a curved sheath that allows the catheter and balloon as well as removal of instruments (Fig. 3.10). The balloon is designed for endovascular use; the delivery catheter was purposely shortened to 100 cm to facilitate its use in this off-label application. Experts are still working on smaller diameter atraumatic instruments although they are not ready for clinical use. The whole fetal surgical procedure is shown in Fig. 3.11.

In severe cases, the FETO task force initially proposed insertion of the balloon at 26–28 weeks and for moderate cases at 30–32 weeks. Earlier occlusion has been done but was prone to more complications. Reversal of occlusion is proposed at 34 weeks. This has been achieved by fetoscopy (50%) or ultrasound-guided puncture (19%). Removal at birth can be done on placental circulation; only in rare cases, it has been done postnatally by direct laryngoscopy or percutaneous puncture.

Table 3.1 Monogenic syndromic conditions frequently associated with congenital diaphragmatic hernia

Syndrome	OMIM	Inheritance	Locus	Phenotype
Cornelia de Lange syndrome	122,470	AD	5p13	IUGR, micromelia, facial dysmorphisms, mental retardation, hirsutism
	300,560	XL	Xp11.2	
Cranio-fronto-nasal dysplasia	304,110	XL	Xq12	Craniosynostosis, hypertelorism, bifid nose, musculoskeletal anomalies
Donnai–Barrow syndrome	222,448	AR	2q24.3 3-2q31	Hypertelorism, corpus callosum agenesis, neurosensorial deafness, developmental delay, proteinuria
Fryns syndrome	229,650	?	?	Typical facies, CNS anomalies, genitourinary anomalies, CHD, distal digital hypoplasia
Matthew Wood syndrome	601,186	AR	14q24.1	Microphthalmia, CHD, genitourinary anomalies
Spondylo-costal dysostosis (Jarcho–Levin syndrome)	277,300	AR	19q13	Short stature, hemivertebrae, vertebral fusion, costal abnormalities
Simpson–Golabi–Behmel	312,670	XL	Xq26	Accelerated growth, abnormal facies, vertebral anomalies, acral anomalies, renal anomalies

Source: Modified from Pober BR, *Clin Genet* 74, 1–15, 2008
AD autosomal dominant; *AR* autosomal recessive; *XL* X-linked; *CHD* congenital heart disease; *CNS* central nervous system; *OMIM* (*Online Mendelian Inheritance in Men*) website

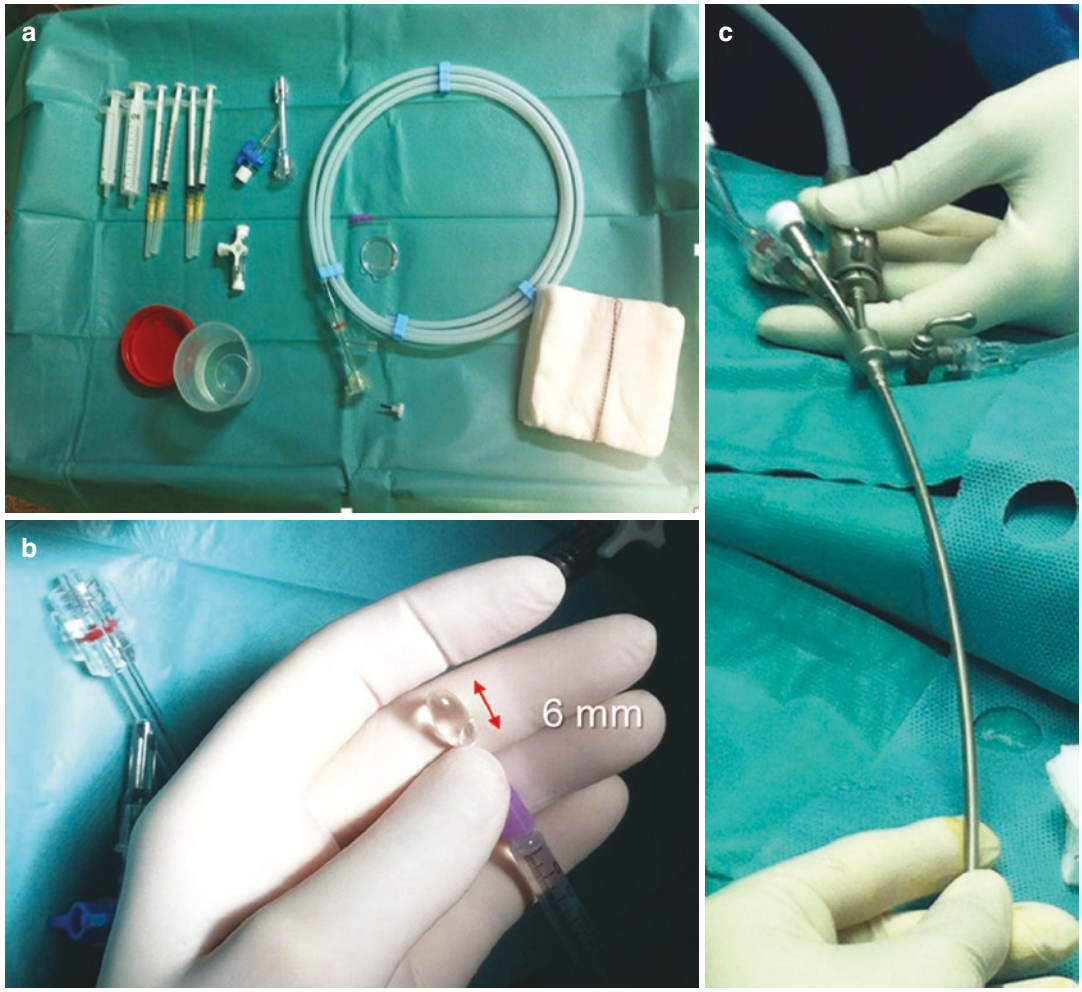

Fig. 3.10 FETO (Fetal Endoscopic Tracheal Occlusion). Instruments employed in the operation are shown. (**a**) the operating room tray; (**b**) the 6 mm balloon which is enflated into the fetal trachea to block it; (**c**) the fetoscope cannula, which includes the optics and an operating channel which contains the deflated balloon mounted on the top of a wire. The size of the cannula is 3 mm

Early delivery is the most relevant complication. It typically is the consequence of Preterm Premature Rupture of the Membranes (p-PROM), which occurs within 3 weeks in 16.7%. Patients with p-PROM are admitted with prophylactic antibiotics and closely watched for signs of infection or other complications that mandate delivery. While overall gestation at delivery was 35.3 weeks, the current experience shows that one in three delivers prior to 34 weeks. This creates the need for emergency balloon retrieval. Especially in these emergency situations, reversal of occlusion should not be underestimated. An unprepared, inexperienced team may be unable to or have difficulties with reversal of occlusion, leading to neonatal death or cause tracheal damage. It does require adapted instrumentation but also trained personnel that is available 7/7 and 24/24.

Compared to historical controls from the antenatal CDH registry, FETO increased survival in severe left-sided CDH from 24.1% to 49.1% ($P < 0.001$) [19]. In right-sided CDH, survival increased from 0% to 35%. Short-term (neonatal) morbidity is better than expected in same severity expectantly managed cases. It is close to that of

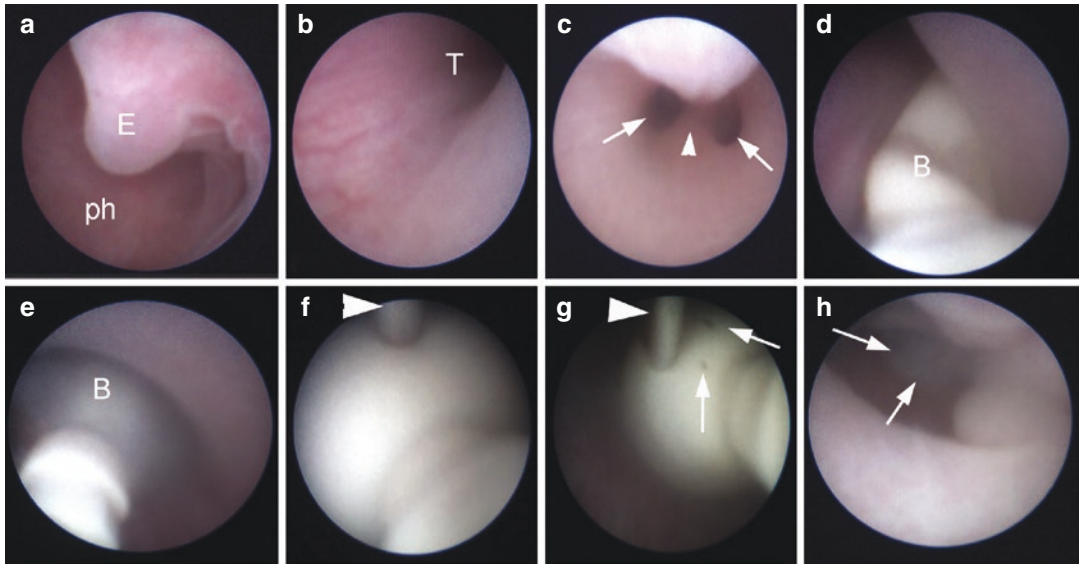

Fig. 3.11 FETO (Fetal Endoscopic Tracheal Occlusion). The sequence of images demonstrates the fetoscopic procedure. (**a**) the epiglottis is shown and, behind that, the pharynx (ph); (**b**) after passing the vocal cords, the trachea (T) is entered with the fetoscope; (**c**) the instrument is cautiously advanced until the carina (arrowhead) with the proximal portion of the two bronchi (arrows) becomes visible; (**d**) the fetoscope is then retracted and the balloon (B) is deployed in the trachea and inflated; (**e**) the balloon (B) is then released, and the operator awaits few seconds to confirm that it remains in place. In the image, the valve of the balloon is clearly visible in the lower part of the image; (**f**) after several weeks in place, if there is no complication which makes the endoscopic retrieval impossible (eg p-PROM or active labor), the procedure is repeated and, once the balloon comes into view, it is punctured with a sharp tipped wire (arrowhead); (**g**) sometimes, more than one punctures are needed to make it deflate. In this image, the wire (arrowhead), making a second hole, and another two holes (arrows) are visible; (**h**) once the balloon is punctured, the high pressure of the fluid trapped in the bronchi and distal trachea leads to the fast ejection of the deflated balloon towards the oral cavity. Following the unplug, some mucus (arrows) becomes visible. This is considered by some authors to be a sign of an effective response of the lung growth to the plug

cases with moderate pulmonary hypoplasia. The ability to remove the balloon more than 24 h prior to birth was, next to a better survival, also associated with lower morbidity. The latter is the reason why we still adhere to a policy of prenatal balloon retrieval, if clinically possible.

The early clinical experience has shown few demonstrable clinical side effects of the balloon on the developing trachea, except in very early occlusions and complications arising at the time of removal. However, the neonates and infants do have obvious tracheomegaly, which becomes less important over time; it does not seem to have a clinical impact, except for a barking cough on effort. Over 70% of newborns require surgical patching of the diaphragm, indicating the rather large size of the defect in this selected group.

Currently, the European FETO Consortium is leading a randomized clinical trial on FETO in moderate CDH, too. The rationale of this trial is that the mortality for moderate hernias is still significant (about 40%); therefore, it was thought that perhaps also in this subset of patients with less severe CHDs, FETO might reduce mortality. Since prematurity is an important concern, it was decided to carry out the plug at 30–32 weeks, rather than at 27–29 as in severe cases.

A comprehensive website (www.totaltrial.eu) is available both for patients and for clinicians.

Delivery. As to the timing and mode of delivery, in the past, it had been apparently shown that delivery by Cesarean section was associated with a better outcome. However, none of the more recent studies has confirmed this apparent advan-

tage of the operative delivery. As a result, currently, there is no recommendation to deliver fetuses with CDH by Cesarean section [3]. In any case, it is true that CDH is a complex malformation requiring multidisciplinary management. Therefore, in several hospitals, as in Gaslini Children's Hospital, the delivery of fetuses with CDH is through a Cesarean Section electively performed in the operating theater of the intensive care unit, following the well-known concept of the DRICU (delivery room in the intensive care unit). There are also some interesting data—albeit by a single group—regarding the timing of delivery. In a recent—but single—study, survival was significantly higher for deliveries occurring later than 40 weeks of gestation than for those occurring at 38–40 weeks [20].

3.3 Congenital Cystic Adenomatoid Malformation of the Lung (C-CAML)

Definition. Congenital Cystic adenomatoid malformation of the lung (C-CAML) is a developmental anomaly of the lung characterized by a mass of disordered pulmonary parenchyma with the proliferation of terminal respiratory bronchioles and a lack of normal alveoli. It is thought to represent a hamartomatous lesion. Histologically, it is classified according to the dimensions of the cysts (Stocker classification; ref. [21]: type I, with large cysts (2–10 cm); type II, with small cysts (0.5–2 cm); and type III, solid or microcystic (<0.5 cm).

Etiology and pathogenesis. The etiology of CAML is unknown. As already mentioned, this lesion represents a developmental anomaly. Histologically, it involves one lobe only, although in US it appears to extend to the whole lung due to its usually large dimensions. It is interesting to note that, on histology slides following surgical removal of the mass, CAML is found to be associated with pulmonary sequestration or segmentary bronchial atresia in a not insignificant percentage of cases. On the basis of these findings, it has been hypothesized that a common pathogenetic mechanism may be responsible for the three different anomalies.

Ultrasound diagnosis. This is performed on the classic *four-chamber view*. Because the histologic Stocker classification cannot be applied to the US appearance, a simpler US-based classification was developed by Wilson et al. [22], which recognizes a cystic and a solid variant or microcystic. The US appearance is completely different for the two types of lesion. The cystic variant appears as a multilocular lesion with cysts of various sizes from a few millimeters to more than 10 mm, which show bright contours due to the posterior wall US enhancement (Fig. 3.12). In contrast, the solid, microcystic variant appears as a well-defined homogeneously hyperechogenic mass (Fig. 3.13). Both types are unilateral by definition (only 3% of CAML cases involve both lungs), and usually of large volume, which causes a contralateral shift of the mediastinum and the heart. In the case of right-sided CAML, there is an abnormally increased cardiac axis due to the extreme levorotation (Fig. 3.12a). The three-dimensional US may be used to evaluate better the volume of the mass and, possibly, to assess the net volume of the cystic component.

Differential diagnosis. The differential diagnosis should be considered for the cystic variant, CDH, as already mentioned: the intrathoracic stomach may, to some extent, resemble a single cyst in a CAML. With regard to the solid variant, the most difficult diagnosis to differentiate in CAML form is pulmonary sequestration. The only US feature that may allow discrimination between the two lesions, which share a highly hyperechoic and homogeneous appearance and mainly unilateral involvement, is the feeding artery, which is ubiquitous in pulmonary sequestration. This is detectable in most cases of pulmonary sequestration using power Doppler or color Doppler with a low-pulse repetition frequency in order to visualize low-velocity vessels: the artery feeding the sequestration is commonly seen branching off the descending aorta. Theoretically, also, a right-sided hernia with liver up should be differentiated from the solid, microcystic variant of CAML; however, in

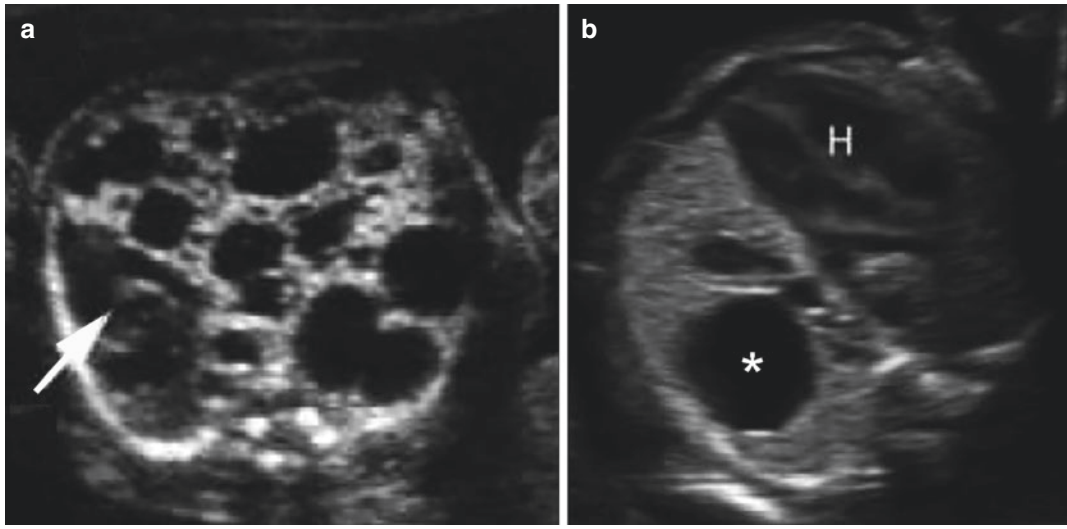

Fig. 3.12 Cystic adenomatoid malformation of the lung (CAML), macrocystic type (22 weeks of gestation). The mac- rocystic type is characterized by one or more cysts of various sizes. (**a**) In this case, the lesion was so large as to com- press the heart (arrow) against the left thoracic wall; (**b**) another case of left-sided macrocystic CAML characterized by a single dominant cyst (asterisk). The heart (*H* heart) is displaced contralaterally

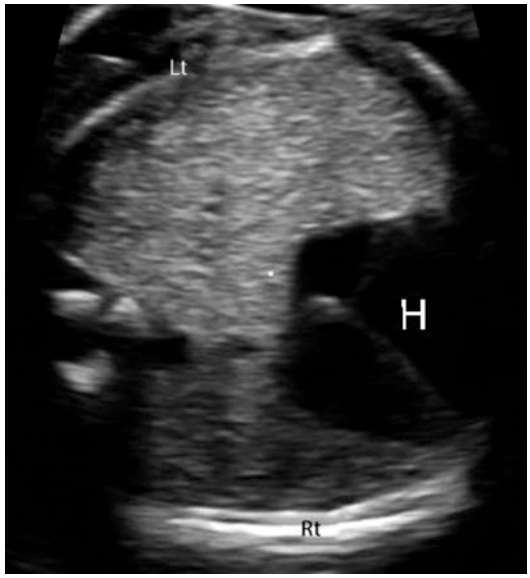

Fig. 3.13 Cystic adenomatoid malformation of the lung (CAML), solid or microcystic type (26 weeks of gestation). If the lesion appears homogeneously hyperechoic, with no visible cysts, the CAML is defined as microcystic, and has to be differentiated from pulmonary sequestration, which has similar sonographic features (see Fig. 3.15a). *Lt* left side, *H* heart, *Rt* right side

this case, the weak echogenicity of the liver is significantly different from the bright appearance of the CAML.

Prognostic indicators. CAML is not usually associated with syndromes, and, therefore, the risk of more severe underlying conditions of prognostic significance is not an issue. The only significant prognostic factor, which allows identification of cases at high risk of perinatal demise, is the occurrence of hydrops (ascites and/or hydrothorax) at the time of diagnosis or during follow-up. It has been hypothesized that the development of hydrops is a consequence of central venous compression, but direct vena cava obstruction is not found in all cases with hydrops. Fortunately, this poor prognostic sign is found in less than 10% of the cases at diagnosis [23], although it can develop in another 30% of cases during follow-up [24]. If hydrops is present, the chances of survival are very low, with perinatal demise being by far the most frequent outcome [25, 26]. Recently, another promising prognostic index derived from the 3D assessment of CAML has been investigated: the *CAM volume ratio*

(CVR) [24]. This parameter is calculated by dividing the volume of the CAML lesion by the circumference of the head, similar to LHR in CDH. In a prospective study [24], the incidence of hydrops was 75% for CVR >1.6 and 17% for CVR <1.7; the latter value dropped to 2.3% if cases with a dominant cyst were excluded. Hence, it seems that for the cystic subtype of CAML, regardless of the volume of the mass, hydrops is more likely to occur if there is a dominant cyst (Fig. 3.12b).

Association with other malformations. There is a strict histologic and pathogenetic relationship with pulmonary sequestration, with the two lesions often being found at histology in the same gross pulmonary lesion. CAML may also be associated with other pulmonary or thoracic anomalies, such as CDH, duplication cysts, tracheoesophageal fistulas, and pulmonary artery branching abnormalities.

Natural history. It is important to underscore that CAML represents an evolving lesion with peculiar features. First of all, the growth of the mass shows a predictable course, with rapid growth occurring between 20 and 26 weeks of gestation. After that period, the volume of the mass plateaus, in a significant percentage of cases, tends to regress or sonographically disappear during the third trimester of pregnancy. Therefore, since the volume of the mass is not expected to grow further after 26 weeks, if there is no hydrops by that gestational age, then it is highly unlikely that this will develop afterward. In addition, it has to be emphasized that, in a significant proportion of apparently vanished lesions, the mass is still present and can be detected by MRI: It has only become invisible in the US, since it has become isoechogenic with adjacent normal lung parenchyma. Overall, 10–20% of cases really do regress almost completely during the third trimester of pregnancy.

Risk of chromosomal anomalies. This is extremely low (anecdotal reports only). In all reports in which a slight increase in the risk of chromosomal anomalies was detected, extrapulmonary malformations were constantly associated.

Risk of nonchromosomal syndromes. This risk is extremely low.

Obstetric management. Should a CAML be detected in a fetus, it is of the utmost importance to search further for very early signs of hydrops. As far as karyotyping is concerned, considering what has already been expressed, we deem this necessary only if other extrapulmonary anomalies are found. An important issue, in our opinion, is to accurately emphasize during prenatal counseling sessions the relatively high rate of spontaneous regression and the consequently very good outcome that these lesions show [23, 25, 26]. The abovementioned prognostic tools (i.e., CVR and presence of hydrops) may be employed at diagnosis and at follow-up US examinations to predict the risk of developing hydrops and consequently identify the fetuses who can benefit from intrauterine treatment. In fact, survival rates, which are excellent in the absence of complications, drop significantly if fetal hydrops is present [25, 26].

Prenatal treatment. This treatment should be limited to those cases in which hydrops develops as a result of increased intrathoracic pressure and is represented by the placement of a thoraco-amniotic shunting device. One of the most commonly used ones is represented by a double pigtail (Fig. 3.14). It is inserted through a 17G needle, after fetal curarization. The distal end is released in the pleural cavity, distended by the effusion while the proximal end is released in the amniotic fluid. The shunt should be inserted on the posterior or postero-lateral part of the ribcage because, if it is inserted anterolaterally, the fetus often removes it with his hands. This procedure has been demonstrated to improve significantly the outcome of fetuses with CAML complicated by hydrops [22]. In selected cases in which there is a single large cyst responsible for the hydrops, the distal end of the shunt can also be released in the cyst itself [26].

Delivery management. There is no contraindication to spontaneous delivery at term in the overwhelming majority of cases. Only in the few instances complicated by fetal hydrops in which either it was not possible to centralize the fetus to tertiary referral centers before the last weeks of pregnancy or the shunts were non-functional because of removal by the fetus or obstruction, it might be considered to setup a Cesarean Section in a DRICU, as for CDH, in order to facilitate early neonatal management.

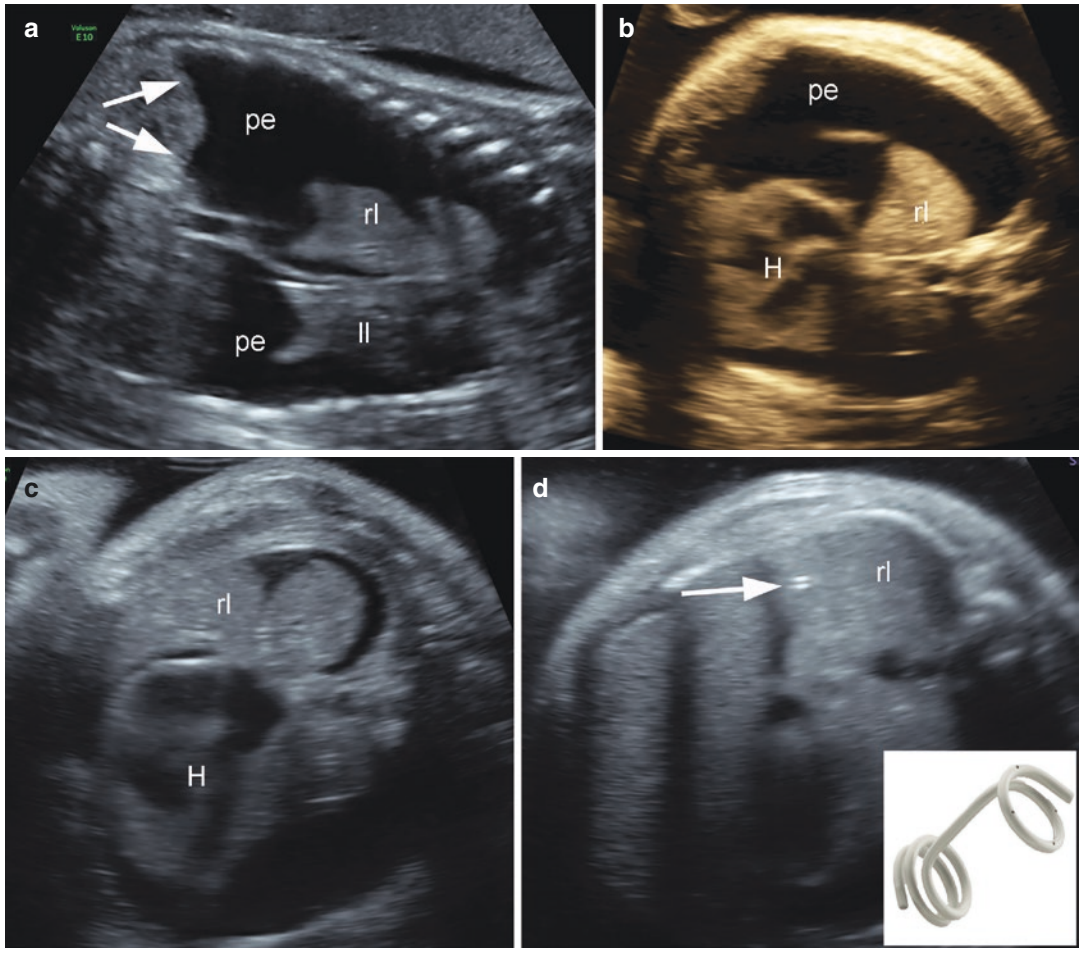

Fig. 3.14 Cystic adenomatoid malformation of the lung (CAML, 26 weeks), shunt placement. In this case, there was severe hypertensive bilateral pleural effusion. (**a**) on the coronal plane, the bilateral hydrothorax and the indentation of the diaphragm (arrows) is shown; (**b**) on the corresponding axial view at the level of the 4-chamber view of the fetal heart, the severe pleural effusion is shown; (**c**) few hours after placement of a thoracoamniotic shunt within the right pleural cavity, the amount of fluid has already significantly decreased; (**d**) after 24 hours, there virtually no more fluid, and the intra-pleural part of the shunt is visible as two tiny hyperechoic lines (arrow). The inset shows the double pigtail shunt (Cook ltd) that we emply in these cases cyst. (*H* heart, *ll* left lung, *rl* right lung, *pe* pleural effusion)

3.4 Pulmonary Sequestration (PS)

Definition. Pulmonary sequestration (PS) consists of an island of the lung parenchyma that does not communicate with the bronchial tree and is fed by the systemic rather than the pulmonary circulation. There are two types of PS: intralobar and extralobar. Prenatal diagnosis of the intralobar variant is quite rare; most cases detected prenatally are represented by the extralobar variant. The extralobar variant is further subdivided into a supra-diaphragmatic and a sub-diaphragmatic subtype, the former accounting for 90% of extralobar PS and the latter for the remaining 10%. The lesion is characteristically unilateral and involves the left lower lobe in 90% of cases. In general, PS shows a roughly triangular shape, with the apex pointing toward the mediastinum. Typically, extralobar sequestrations present a feeding artery branching off the descending thoracic or abdominal aorta.

Etiology and pathogenesis. The etiology of PS is unknown, although it has been suggested that it might share the pathogenesis with CAML due to the fact that the two lesions are frequently associated.

Ultrasound diagnosis. This is carried out on the *four-chamber view* given that the lesion often involves the left lower lobe, which is at the same level as the heart, or just below. PS appears as a well-defined, homogeneously hyperechoic, roughly triangular mass, often involving the lower part of the left lung (Fig. 3.15a). Only the subdiaphragmatic variant may not be readily recognizable on the four-chamber view, and instead requires a lower axial or parasagittal view, at the level of the diaphragm (Fig. 3.15b). To complete the US assessment, it is necessary to switch to *sagittal views* because only these allow: (1) assessment of the caudal extension of the mass; (2) detection and characterization of subdiaphragmatic extralobar sequestrations (Fig. 3.15b); and (3) recognition, on power or color Doppler, of the feeding artery branching off the descending aorta (Fig. 3.15c). Finally, the possible association of ipsilateral hydrothorax (Fig. 3.16), frank hydrops,

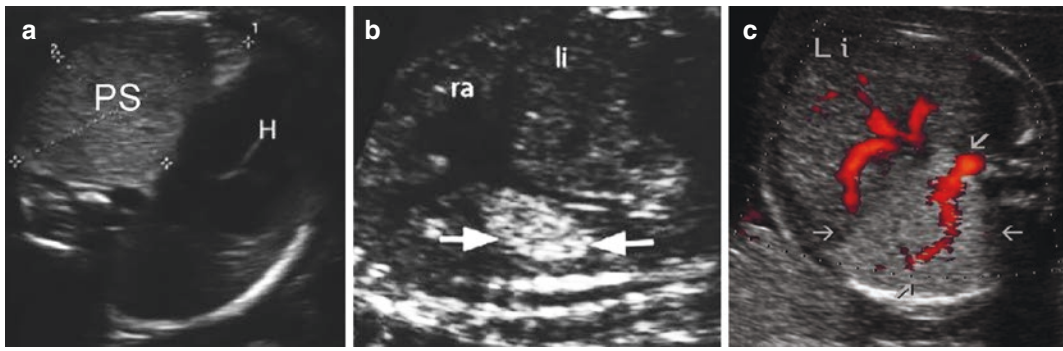

Fig. 3.15 Pulmonary sequestration, extralobar type. This anomaly has a hyperechoic aspect and, often, a triangular shape. It can be located in the thorax or below the diaphragm. (**a**) Supradiaphragmatic pulmonary sequestration (25 weeks of gestation): the axial view of the thorax demonstrates the homogeneously hyperechoic lesion (PS) of the left lung (calipers); the heart (H) is displaced in the right hemithorax; (**b**) subdiaphragmatic pulmonary sequestration (22 weeks of gestation). The right parasagittal thoracic view demonstrates the subdiaphragmatic location of the sequestration (arrows); (**c**) (*li* liver); (**c**) The vascular pedicle can be recognized in all cases. Color or power Doppler with a low pulse repetition frequency are used to locate the feeding artery, which, in most instances, branches off the thoracic or abdominal aorta. In this case, on the axial view of the upper abdomen, the feeding artery is seen branching off the abdominal aorta. The arrows indicate the hyperechoic sequestration. (*Li* liver)

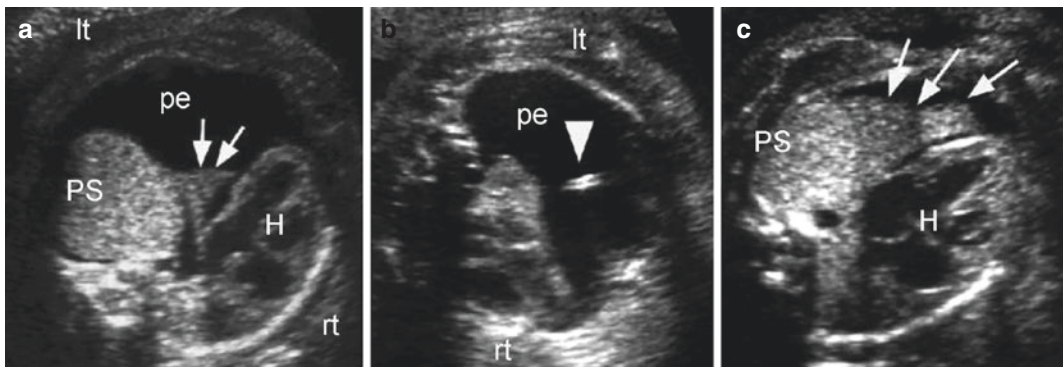

Fig. 3.16 Pulmonary sequestration, extralobar. In some cases, pulmonary sequestration is associated with hydrops. In these cases, the placement of a thoracoamniotic shunt may resolve the hydrops due to venous compression. (**a**) The supra-diaphragmatic pulmonary sequestration (PS) is shown, associated with a severely hypertensive hydrothorax, compressing the left lung (arrows). (**b**) This image shows the intra-pleural part of the shunt (arrowhead) inserted to drain the pleural effusion. (**c**) After few hours, the pleural effusion has almost disappeared, and the left lung has re-expanded (arrows). The different echogenicities of the sequestration (PS) and the lung are also evident. Note the heart displaced in the right hemithorax. (*H* heart, *lt* left side, *pe* pleural effusion, *rt* right side)

or other thoracic malformations (e.g., a CDH) should be excluded.

Differential diagnosis. As already mentioned, difficult differential diagnosis is with the solid, microcystic variant of CAML due to the very similar echogenicity of the mass. However, a more triangular shape, a location in the left lower lung area, and, above all, the recognition of the feeding vessel (Fig. 3.15c) all favor a PS. With the rare subdiaphragmatic subtype of PS, the differential diagnosis should include rare tumors (e.g., hemangiomas and neuroblastomas). It should be noted that in the very rare instance in which a feeding vessel is identified entering the solid component of a prevalently cystic CAML, the lesion is probably a case of mixed CAML + PS lesion.

Prognostic indicators. As for CAML, the occurrence of hydrops is the most ominous prognostic indicator. However, there have been cases (although rare) in which with the spontaneous regression of the PS, the hydrops has also disappeared, with a good perinatal outcome.

Association with other malformations. The close histologic and pathogenetic relationship with CAML has already been emphasized. PS, like CAML, may also be associated with other pulmonary or thoracic anomalies, such as CDH, duplication cysts, tracheoesophageal fistulas, and pulmonary artery branching abnormalities.

Natural history. The tendency to regress and even disappear during the third trimester has also been reported for PS, which further supports the close pathogenetic links with CAML. In some series, this tendency has been shown to be even more pronounced than that reported for CAML, occurring in 30% of cases [27, 28].

Risk of chromosomal anomalies. This risk is extremely low.

Risk of nonchromosomal syndromes. This risk is extremely low.

Obstetric management. Given that the risk of chromosomal anomalies is low, karyotyping is not mandatory in the case of isolated PS. What should be monitored is the possible presence/onset of hydrothorax or hydrops. In most cases, the hydrops is a consequence of the hypertensive hydrothorax that can occasionally complicate PS. In fact, the hydrops often disappears after placement of a thoraco-amniotic shunt, which reduces the high intrathoracic pressure. The possibility of spontaneous regression and a good outcome also in cases complicated by hydrops should be communicated to the parents during prenatal counseling [27, 28].

Prenatal treatment. This is the same as for CAML and consists of placing a thoraco-amniotic shunting device that drains the fluid continuously produced in the pleural space into the amniotic cavity (Fig. 3.16). The intervention has already been described in the CAML section.

Delivery management. This is managed as for CAML, so the reader is referred to that section for details.

3.5 Bronchial Atresia

Definition and anatomy. *Bronchial atresia* is defined as a focal obliteration of a proximal segmental or subsegmental bronchus that lacks communication with the central airways. Generally, a distal segment persists, and it may dilate as a consequence of entrapment of the fluid produced by the alveoli.

Etiology and pathogenesis. The more accepted pathogenetic theory for this kind of lesion implicates the impaired blood supply during the embryogenetic period, which may have prevented the normal development of the affected bronchial segment.

Ultrasound diagnosis. This is carried out on the axial four-chamber view of the thorax. The heart and the mediastinum are severely displaced contralaterally by a huge pulmonary hyperechoic mass (Fig. 3.17). The lung tissue is hyperechoic due to entrapment of the fluid produced by the alveoli, and, in some cases, the distal segments of the bronchus, dilated by the entrapped fluid, are visible, too.

Differential diagnosis. Both the microcystic, solid variant of CAML and PS should be differentiated from bronchial atresia due to the homogeneously increased echogenicity of the lung mass. However, in bronchial atresia, the volume of the mass is generally much larger than with the

other two entities, and, in addition, part of the distal bronchus is visible as a sonolucent segment (Fig. 3.17), in most cases. Another easy differential diagnosis is laryngeal atresia. However, in the latter, both lungs are enlarged and hyperechoic, while bronchial atresia is a unilateral lesion.

Prognostic indicators. Should ascites be associated, this represents a sign of central venous compression and, as such, it bears a poor prognostic sign.

Association with other malformations. Developmental anomalies involving other parts of the bronchial tree and/or esophageal abnormalities may be associated.

Risk of chromosomal anomalies. This risk is extremely low.

Risk of nonchromosomal syndromes. This risk is extremely low.

Obstetric management. Karyotyping is not indicated because of the low risk of aneuploidy.

Fetal surgery. This has been carried out successfully in one case only [29]. It was a case of mainstem bronchus atresia, with the distal bronchus dilated and visible. The operator could access the blindly ending bronchus with the same instruments and procedure described for FETO in the diaphragmatic hernia (see that section for details). However, once the blind end of the bronchus was reached, the laser was used to carefully create a tunnel and reach the distal part of the bronchus. The procedure was successful.

Delivery management. Delivery should take place in a referral center, due to the likely need for immediate aggressive neonatal resuscitation and intubation, considering the common association of hydrops and the extremely large volume of the mass.

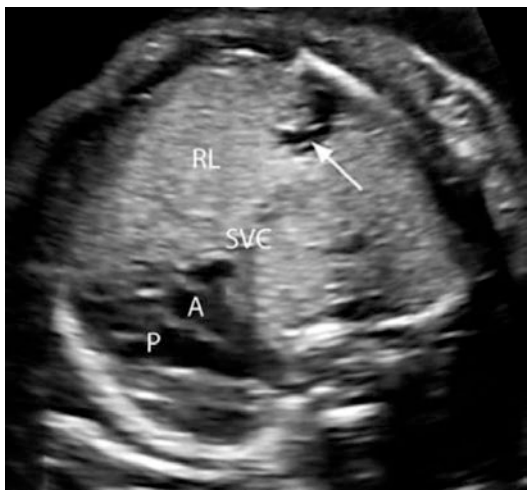

Fig. 3.17 Bronchial atresia (25 weeks of gestation). On the axial three-vessel view, the severe mediastinal shift is evident, with the whole thorax occupied by the grossly enlarged and hyperechoic right lung (RL). Dilatation of distal bronchi is also visible (arrow). (*A* aortic arch, *P* pulmonary artery and ductal arch, *SVC* superior vena cava)

3.6 Laryngeal Atresia

Definition. Laryngeal atresia is an exceedingly rare anomaly consisting of three possible lesions: agenesis of the glottis, agenesis of the larynx, or agenesis of both. As a result of any of the three anomalies, the high airways are completely obstructed, and this leads to the inclusion of laryngeal atresia among the lesions causing CHAOS.

Etiology and pathogenesis. The more accepted pathogenetic theory for this kind of lesion implicates the impaired blood supply during the embryogenetic period, which may have prevented the normal development of the trachea/larynx.

Ultrasound diagnosis. The differentiation between laryngeal and tracheal atresia is not feasible on US. The diagnosis is made on the *four-chamber view of the fetal heart*. Typically, *both* lungs appear severely enlarged and highly hyperechoic (Fig. 3.18). Owing to the exceedingly high intrathoracic pressure, the heart is squeezed in between the lungs and appears smaller than it actually is due to the degree of pulmonary enlargement. It shows a reduced (sometimes to zero) cardiac axis. Relatively often, some fluid is trapped in the bronchial tree and is responsible for the bronchogram (dilatation of the trachea and bronchi by the entrapped fluid that can sometimes be present). In this case, the swollen trachea appears as a small round sonolucent area behind the heart. The bronchogram, if present, is better displayed with a *coronal approach*: On this view, the dilated trachea is seen bifurcating at the

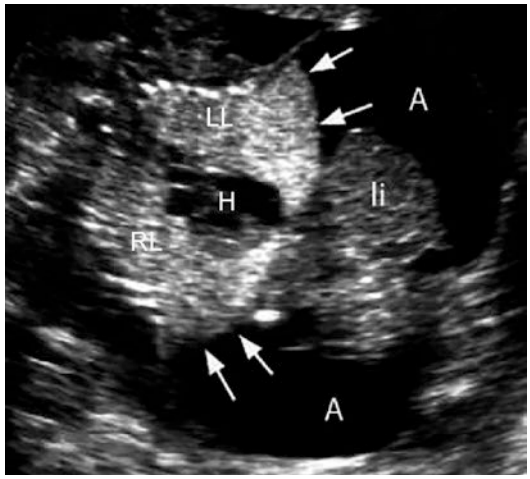

Fig. 3.18 Laryngeal atresia (22 weeks of gestation). (The coronal view of the fetal trunk demonstrates eversion of the diaphragm (arrows), due to the massive enlargement of the lungs, and ascites, which is almost ubiquitous in laryngeal atresia. (*A* ascites, *H* heart, *li* liver, *LL* left lung, *RL* right lung)

level of the carina in the two bronchi. On the coronal view of the fetal thorax and abdomen, at low magnification, the severe bell-shaped distortion of the thorax, the flattening or inversion of the diaphragmatic convexity, and the ubiquitous ascites can be appreciated (Fig. 3.18).

Differential diagnosis. There is virtually no differential diagnosis to be made since laryngeal atresia represents an absolutely unique lesion in the US. Seen once, it will never be forgotten! The extremely rare cases (<3%) of bilateral, solid, microcystic ACML would not show the severely increased lung volume typical of laryngeal atresia.

Prognostic indicators. The lethality of this condition makes the identification of poor prognostic signs not applicable. If anything, the detection of severe oligoamnios due to concurrent renal agenesis together with other major anomalies characterizing *Fraser syndrome* makes the prognosis even worse than it already is, considering that the latter is transmitted as an autosomal recessive trait [30].

Association with other malformations. Developmental anomalies involving the bronchial tree and the esophagus may be associated.

Risk of chromosomal anomalies. This risk is extremely low.

Risk of nonchromosomal syndromes. This risk is high. A significant proportion of cases of laryngeal atresia are associated with Fraser syndrome [15].

Obstetric management. The possibility of additional anomalies indicating the likely presence of Fraser syndrome should be investigated. In fact, isolated laryngeal atresia is a sporadic malformation, whereas Fraser syndrome shows autosomal recessive inheritance. Karyotyping is not indicated because of the low risk of aneuploidy and the very high mortality rate.

Delivery management. The only available option to try salvaging a fetus with laryngeal atresia is the *EXIT procedure* (***Ex*** utero ***I***ntrapartum ***T***reatment). As of 2018, even with this technique, there are fewer than 10 surviving cases of laryngeal atresia reported in the literature [31].

3.7 Bronchogenic Cyst

Definition and anatomy. Bronchogenic cysts result from an anomalous development of the ventral foregut. More commonly, they are single, but multiple cysts also have been described postnatally. They can occur along the whole tracheoesophageal course but with a predilection for the area around the carina. Those in the mediastinum are frequently adherent to the tracheobronchial tree but do not communicate with it. Bronchogenic cysts have also been described in unusual locations, such as the neck, abdomen, and retroperitoneal space.

Etiology and pathogenesis. Bronchogenic cysts arise from anomalous airway buds that contain nonfunctional pulmonary tissue.

Ultrasound diagnosis. In most cases, the cysts are large enough to be detected on the four-chamber view, where they appear as large, sometimes bilobed anechoic lesions (Fig. 3.19). However, it should be noted that, very rarely, bronchogenic cysts appeared prenatally as hyperechoic lesions.

Differential diagnosis. Theoretically, a cystic thoracic lesion might be a CAML with a domi-

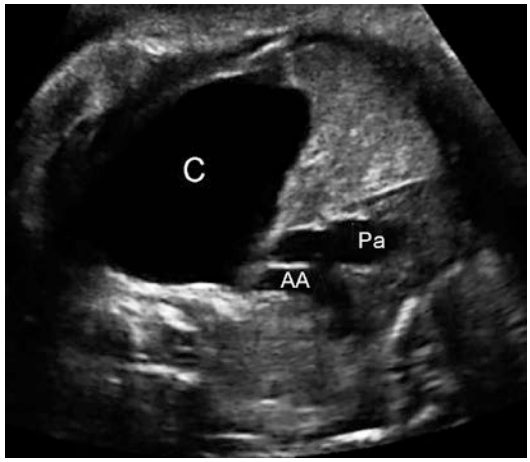

Fig. 3.19 Bronchogenic cyst (29 weeks of gestation). On the axial three-vessel view of the thorax, the large cyst (C) is visible. It displaces the mediastinum and the heart contralaterally, and is not associated with lung hyperechogenicity. (*AA* aortic arch, *Pa* pulmonary artery and ductal arch)

nant cyst or the herniated stomach in CDH. However, in CAML, the tissue surrounding the mass is hyperechoic, which is not the case for the bronchogenic cyst that represents an isolated lesion, and the presence of the stomach in its normal subdiaphragmatic location rules out CDH.

Association with other malformations. Developmental anomalies involving the bronchial tree and the esophagus may be associated.

Risk of chromosomal anomalies. This risk is extremely low.

Risk of nonchromosomal syndromes. This risk is extremely low.

Obstetric management. Karyotype is not indicated because the risk of aneuploidy is virtually nonexistent. Delivery should take place in a referral center because of the possible need for emergency intubation at birth.

3.8 Lung Agenesis/Hypoplasia

Definition and anatomy. The various degrees of pulmonary underdevelopment have been classified into three groups [32]: In group 1, bronchus and lung are absent (agenesis); in group 2, a rudimentary bronchus is present and limited to a pouch without lung tissue (aplasia); in group 3, there is bronchial hypoplasia with a variable reduction in lung tissue (hypoplasia). Most cases of right lung hypoplasia are associated with scimitar syndrome, a rare anomaly in which a moderate-to-severe degree of lung hypoplasia is associated with the partial abnormal venous return into the inferior vena cava.

Etiology and pathogenesis. Lung agenesis is usually unilateral, and it occurs at approximately 4 weeks of gestation when the primitive lung is forming. The etiology of this anomaly is unknown. However, >50% of children with pulmonary agenesis have associated congenital anomalies that involve the cardiovascular, gastrointestinal, skeletal, and genitourinary systems, with most of the limb and spinal anomalies occurring ipsilaterally to the pulmonary agenesis. The contralateral lung is normal in structure but has compensatory hypertrophy.

Ultrasound diagnosis. Lung agenesis: The diagnosis is made on the *axial four-chamber view* of the fetal thorax. The first impression is that of a CDH due to the extreme displacement of the mediastinum and the heart. Once the sonologist notes that there are no abdominal viscera in the thorax and that one of the lung fields is absent, the diagnosis is made. Color Doppler may be used to detect the concurrent absence of the ipsilateral pulmonary branch. *Lung hypoplasia:* In most of the cases detected in the fetus, this anomaly is part of the *Scimitar syndrome*, a condition in which partial pulmonary venous return is associated with lung hypoplasia of variable degree.

Obstetric management. There is no need for karyotyping due to the very low risk of association with chromosomal abnormalities. However, sporadic cases of lung hypoplasia have been associated with microdeletion 22q11; so, if other US signs of these conditions are found—such as a right aortic arch or a conotruncal malformation—an amniocentesis should be performed and a CGH-array should be done.

Delivery management. Delivery should take place in a referral center because early neonatal intubation may be needed in rare cases of lung agenesis, due to tracheal malposition. In scimitar syndrome, only very rarely does the neonate need early intervention or ventilatory assistance.

3.9 Hydrothorax

Definition. This is a fluid pleural effusion. It can be unilateral or bilateral, isolated, or in the context of generalized hydrops.

Etiology and pathogenesis. The etiology is extremely variable, including at one end of the spectrum thoracic causes, such as in chylothorax, and at the other, classic nonimmune hydrops fetalis (NIHF). Thus, hydrothorax shares its pathogenesis with that of NIHF if the pleural effusion represents one of the signs of hydrops. On the contrary, if the pleural effusion is isolated and no other chromosomal or nonchromosomal anomalies are associated, it may be due to a malformation (atresia or fistula) of the thoracic duct (chylothorax).

Ultrasound diagnosis. Hydrothorax can be diagnosed on the *four-chamber view* as a unilateral (Fig. 3.20a) or bilateral (Fig. 3.20b) anechoic area. It usually has a roughly moon-shaped appearance due to the fact that it surrounds the lung, except for the hilum (Fig. 3.20). The *hydrothorax* is defined as hypertensive if the intrathoracic pressure is high, and all viscera are pushed into the contralateral hemithorax (Fig. 3.20a). A significant proportion of isolated, hypertensive, and unilateral hydrothoraces are actually chylothoraces [33]. If the pleural effusion is part of general NIHF, the severe edema of the subcutaneous thoracic tissue can be seen on the four-chamber view (Fig. 3.20a).

Prognostic indicators. The most important prognostic factor in fetuses with hydrothorax is the association with NIHF because in these cases the outcome is generally very poor, with a few exceptions. Another poor prognostic indicator is the association with anomalies at high risk of chromosomal anomalies, such as congenital heart disease or CNS malformations. The absence of any associated malformation and/or of any other fluid effusion possibly indicative of concurrent hydrops is the only good prognostic factor; in fact, in isolated hydrothorax, the placement of a thoracoamniotic shunt has been demonstrated to improve the outcome of hypertensive cases.

Association with other malformations. Congenital heart disease and ipsilateral pulmonary malformations may be associated.

Natural history. Chylothorax can regress in 10–25% of cases, spontaneously or after single drainage [33, 34].

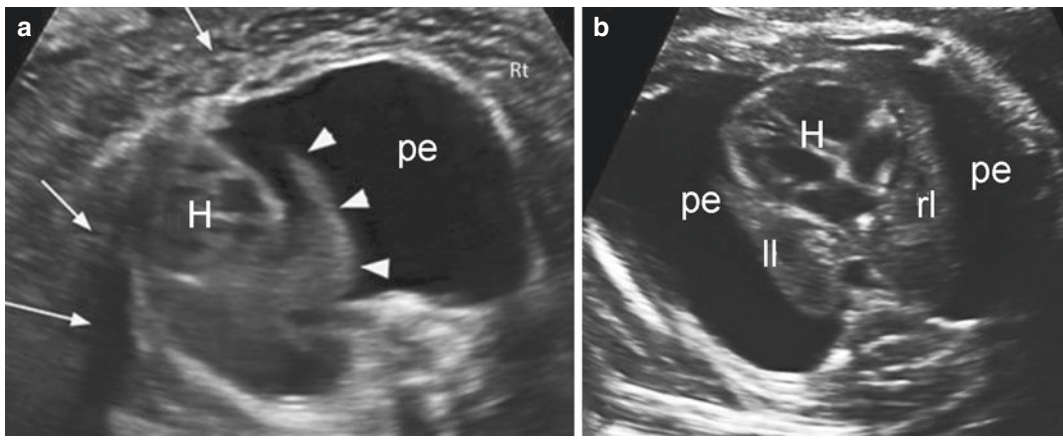

Fig. 3.20 Hydrothorax, unilateral, hypertensive. (**a**) The increased intrathoracic pressure is demonstrated by the fact that both the mediastinum and the lung ipsilateral to the effusion (arrowheads) are pushed into the left hemithorax. This was associated with massive hydrops and severe subcutaneous edema (arrows). (**b**) In other cases, the hypertensive hydrothorax is bilateral. In these cases, a thoraco-amniotic shunt can be placed on the side more severly affected (the left, in this cases), and then it is possible to wait up to a week, to monitor the evolution, because the contralateral effusion may not necessarily need shunting. (*H* heart, *ll* left lung, *pe* pleural effusion, *rl* right lung)

Risk of chromosomal anomalies. This risk is high. The risk applies also to isolated transient hydrothorax, be it early or late third-trimester onset, and concerns mainly trisomy 21 and Turner syndrome (monosomy X). Isolated chylothorax has also been shown to bear a not insignificant risk of aneuploidy (1–6%).

Risk of nonchromosomal syndromes. This risk is high, especially if NIHF is associated. There are several syndromes that may feature hydrothorax. These may be associated with other sonographically detectable anomalies, or, in a few instances, the hydrothorax may represent the only prenatally recognizable sign.

Obstetric management. Should a pleural effusion be diagnosed in a fetus, karyotyping is mandatory due to the high risk of associated chromosomal anomalies. In addition, a thorough anatomic scan should be performed by an expert in order to detect major and/ or minor signs possibly indicative of a syndromic context. If the hydrothorax is isolated, and karyotyping has ruled out any underlying chromosomal aberration, its evolution should be carefully monitored. The detection of signs possibly indicating elevated intrathoracic pressure, such as flattening of the ipsilateral lung and/ or evident mediastinal and heart displacement into the contralateral hemithorax (Fig. 3.20a), may represent an indication for the placement of a thoraco-amniotic shunt. In fact, this procedure has been demonstrated to prevent or reverse the occurrence of hydrops if it is due to hydrothorax. In particular, it has been shown that if the hydrops is a direct consequence of the hypertensive hydrothorax, the placement of a thoraco-amniotic shunt increases the overall survival rate from 10% to 60% [33, 34].

Prenatal treatment. This has been described in the section on CAML. Please, refer to that section for details.

3.10 Mediastinal Tumors/Cysts

Definition. In this section, we include cystic or solid mediastinal lesions not belonging to the heart, the gastrointestinal tract, or the tracheobronchial tree. Hence, most of these lesions are represented by simple cysts (pericardial or neurenteric), or by benign tumors, such as lymphangiomas or teratomas [35, 36].

Etiology and pathogenesis. These are either developmental anomalies (e.g., neurenteric cyst) or benign mesenchymal tumors (e.g., lymphangioma or teratoma).

Ultrasound diagnosis. The diagnosis of mediastinal tumors is made on the two major axial planes of the thorax, the *four-chamber view,* and/ or the *three-vessel view.* The site of the tumor dictates the diagnostic view, although it should be considered that in most cases these tumors are large enough to be visible on all thoracic views. Mediastinal *teratoma* usually originates within the pericardium (Fig. 3.21a) and is responsible for severe pericardial effusions. Another mesenchymal tumor rarely found in the thorax is the *lymphangioma* (Fig. 3.21b), which needs to be differentiated from the macrocystic type of CAML; however, the former is often large enough to present with bilateral cystic areas, which is very unusual for CAML, which is bilateral only in 3% of cases.

Risk of chromosomal anomalies. This risk is low.

Risk of nonchromosomal syndromes. This risk is low.

Prognostic indicators. As for all thoracic and neck masses, the poorest prognostic factors are represented by central venous compression leading to hydrops or high airway compression, which would require an EXIT procedure at birth (see CHAOS).

Association with other malformations. Lymphangiomas, as well as hemangiomas, may have multiple locations, often subcutaneous.

Obstetric management. In nonobstructive lesions, the final diagnosis will be made after birth. MRI may help in challenging cases to differentiate thoracic lymphangiomas from CAML, macrocystic type.

Fetal surgery. In case of cystic lesions leading to hydrops from increased central venous pressure, the placement of a thoracic–amniotic shunt—or even pericardio-amniotic shunt—may represent an option for consideration. The most important task is to define prenatally whether

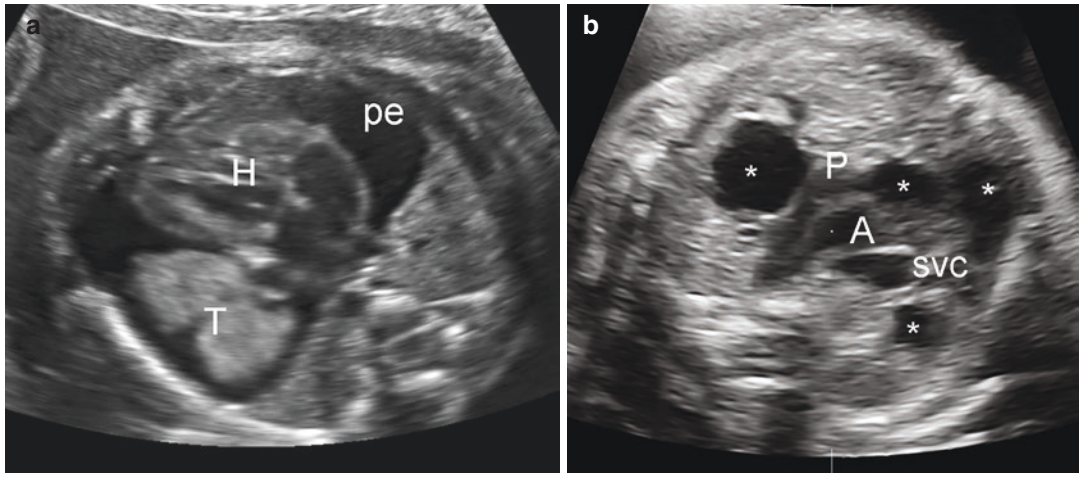

Fig. 3.21 Thoracic tumors. (**a**) Mediastinal teratoma at 32 gestational weeks. On the 4-chamber view of the fetal heart, the tumor (T) is visible to the left of the heart (H). there was severe pericardial effusion (pe). At neonatal surgery, the stalk was identified on the external wall of the main pulmonary trunk; (**b**) Thoracic lymphangioma (29 weeks of gestation). On an upper mediastinal axial view, the various cystic locules of the multicystic tumor are shown (asterisks). Note that all the locules are not within the lung parenchyma but external to it (*A* aortic arch, *P* pulmonary artery and ductal arch, *SVC* superior vena cava)

there is a need for an EXIT procedure due to high airway obstruction [36] and, if so, proceed to in utero transfer to a referral center where this complicated and costly procedure is available.

3.11 Esophageal Atresia (EA) and Tracheoesophageal (TE) Fistula

Definition. In EA, the communication between the proximal and the distal tract of the esophagus is absent due to a lack of development of the intermediate esophageal portion, mainly because of an interruption of blood supply during organogenesis. EA can occur as an isolated anomaly or, much more frequently, be associated with a TE fistula (i.e., an abnormal communication between the trachea and the distal esophageal stump) (about 90% of cases). The frequent association with a TE fistula is responsible for the low intrauterine detection rate: This is due to the fact that some amniotic fluid may actually reach the distal esophagus and eventually fill the stomach, just by transiting through the fistula. If this is the case, then US diagnosis becomes very difficult, based on the detection of a relatively small gastric bubble. Anatomically, five types of EA are recognized, according to the Gross classification [37], on the basis of the anatomy and site of the TE fistula:

- Type A: no fistula (7% of cases);
- Type B: EA with proximal TEF (2%);
- Type C: EA with distal TEF (86%);
- Type D: EA with proximal and distal TEF (1%);
- Type E: TEF without concomitant EA (4%).

Only type A is reliably detectable in the fetus by the nonvisualization of the gastric bubble.

Etiology and pathogenesis. The etiology of the defect is unknown. It originates when, at 8 weeks of gestation, the primitive foregut does not divide into the ventral trachea bronchial part and the dorsal digestive part.

Ultrasound diagnosis. The diagnosis of EA is challenging and is not done prenatally in most cases. The lack of persistent patency of the esophageal lumen and the close proximity of this organ to anatomical structures of similar tissue texture render the sonographic evaluation of the fetal esophagus a difficult task [2]. In addition, it should be underlined that most of the cases of EA

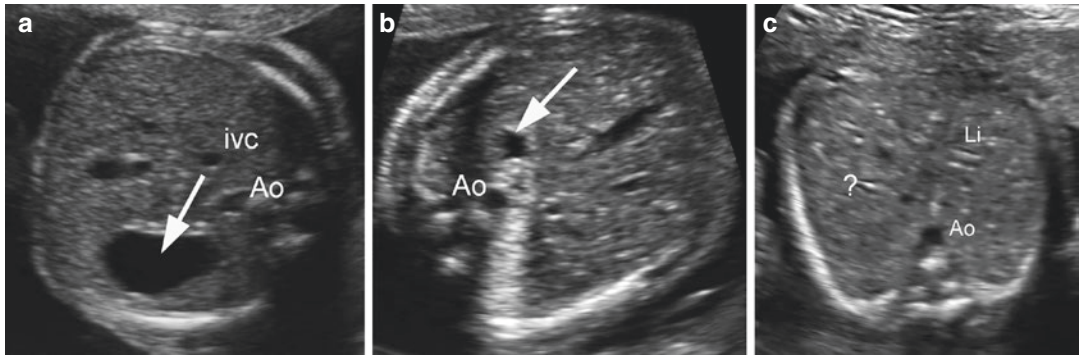

Fig. 3.22 Esophageal atresia. (**a**) the axial view of the fetal abdomen demonstrates the normal size of the stomach at midtrimester (Ao: descending aorta; ivv: inferior vena cava); (**b**) in this case, only a very small stomach bubble (asterisk) was demonstrated on several scans 1 hr apart. If this finding is associated, in the 3rd trimester, with severe polyhydramnios, it may be indicative of esophageal atresia with tracheo-esophageal fistula (Ao: descending aorta); (**c**) in this other case, the stomach bubble could not be demonstrated on several scans on more than 1 hour of observation. This is highly indicative of isolated esophageal atresia (type A, see text)

are extremely difficult to detect in utero due to the presence of a concurrent TE fistula: Usually, this fistula does not prevent a nearly normal stomach-filling; in less frequent cases, a constantly small gastric size is found. In fact, the combination of a small or absent fetal stomach (Fig. 3.22b) with polyhydramnios, which is the most common indirect US findings when EA is suspected prenatally, has a positive predictive value of only 40–56% in diagnosing esophageal obstruction [38, 39], with a high false-positive rate. In addition, a wide range of pathologic conditions may be associated with absent or small gastric bubbles, and all of these should be ruled out before reaching a definite diagnosis of EA. The fact that these anomalies include very severe or lethal conditions, such as FADS, has led some authors to identify persistent nonvisualization of the gastric bubble as a poor prognostic sign per se, being associated with a poor pregnancy outcome in roughly 50% of the cases, regardless of its cause. As reported here, the other sign possibly indicative of EA is polyhydramnios, which becomes clearly evident only in the late second or the third trimester. It can be associated with FGR; it should be underlined that the association between FGR and polyhydramnios is uncommon, the latter usually being associated with fetal macrosomia. The development of FGR, which is present in 35–40% of fetuses with EA, has been thought to be an effect of the reduced intestinal absorption of the proteins present in the amniotic fluid (due to lack of swallowing), which at term can be as high as 2 g protein per day. Another interesting feature is that 50% of the EAs associated with Down syndrome are type A (i.e., without a TE fistula); this is why in the fetus, the recognition of an EA based on absent gastric bubble implies a very high risk of chromosomal anomalies. More recently, visualization of the dilation of the blind-ending esophagus (esophageal pouch) in the fetal neck or upper mediastinum during fetal swallowing has been reported and proposed as a reliable sign for predicting EA. In fact, more than 85% of EA are type C of the Gross classification, with a blind ending of the proximal part of the esophagus. Unfortunately, this ultrasound sign is uncommon before 23 weeks and inconstant in the third trimester. Its identification can imply a detailed and long sonographic examination and depends on the presence of fetal swallowing during the examination. Consequently, failure to identify a pouch in the fetal neck does not exclude EA. However, the association of absent or small gastric bubble, polyhydramnios, and the presence of a pouch, especially if they persist in successive examinations, can significantly increase the likelihood of EA [40]. The accuracy of the prenatal diagnosis of EA might be further improved by 3D US and by magnetic resonance imaging (MRI) [39].

Differential diagnosis. This includes all conditions possibly associated with absent or small gastric bubble: severe oligohydramnios (and con-

sequent lack of amniotic fluid ingestion) in the case of premature rupture of membranes or bilateral renal agenesis, FADS and related syndromes, diaphragmatic hernia, and cleft lip and palate.

Prognostic indicators. Association with other major anomalies, which is fairly common, represents the most important poor prognostic sign, since the occurrence of concurrent anomalies makes surgical correction of the defect more difficult. In addition, the frequent occurrence of a low birth weight, as a result of FGR, may render the outcome even more guarded.

Association with other malformations. Major anomalies are associated in 40–70% of the cases, with prevalence, in decreasing order, of GI tract (28%), cardiovascular (24%), genitourinary (13%), and osteomuscular (11%) malformations. The VA(C)TER(L) association (the "TE" of which stands for TE fistula) accounts for a significant number of these anomalies.

Risk of chromosomal anomalies. This is high, reaching 20–44% of cases in the fetus, with a prevalence of trisomies 21 and 18. This high risk is related to the fact that mainly type A EA (atresia without concurrent TE fistula), which is the one most frequently associated with Down syndrome, is usually diagnosable in utero.

Risk of nonchromosomal syndromes. This is relatively high and relates to the possible presence of an underlying VA(C)TER(L) association.

Obstetric management. Should EA be suspected in a fetus, a thorough anatomic scan should be performed by an expert in order to detect major and/or minor signs possibly leading to the diagnosis of one of the associated anomalies discussed in this chapter. Fetal karyotyping is also mandatory because of the high risk of Down syndrome and, to a lesser extent, of trisomy 18.

Delivery management. The delivery should take place in a tertiary referral center, where a neonatal intensive care unit (NICU) and pediatric surgery are available. The need for in utero transport arises from various considerations: (1) the consistent risk of associated FGR (40% of cases) and prematurity (due to polyhydramnios), which may require NICU admission; (2) the possibility that other major anomalies overlooked at prenatal US may be present; (3) the need for adequate preoperative nutrition; and (4) the need for early corrective surgery.

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Imaging of the Chest

4

Maria Beatrice Damasio, Francesca Rizzo,
Fiammetta Sertorio, and Lorenzo Anfigeno

4.1 Introduction

Imaging of the chest in paediatric patient allows visualization of the anatomy and function of the lungs and the detection of congenital and acquired cardiopulmonary disorders.

4.2 Radiography

Chest radiographic examination is the most routinely performed radiologic exam in paediatric patients. The appropriate radiographic technique is of paramount importance for diagnosis (1).

The supine anteroposterior (AP) view is routinely used for young infants, whereas toddlers are generally examined in a standing PA view. Additional views can be useful to assess pleural effusion, pneumothorax and foreign bodies. Proper positioning of both patient and X-ray tube is extremely important to avoid a distorted chest image. Cranial angulation (Fig. 4.1) of the tube can result in a bizarre configuration of the ribs and gross distortion of the chest, simulating a bone dysplasia, whereas lordotic positioning (Fig. 4.2) of the patient produces an abnormally prominent cardiac apex, simulating right ventricular hypertrophy as seen in Tetralogy of Fallot. Lordotic positioning can be recognized by the horizontal pattern of the posterior ribs [1–3]. Hyperlucency of one lung can be seen when the patient is rotated to one side and should not be misinterpreted as a pathological finding (Fig. 4.3). To ensure that the chest is not rotated, the operator should verify that the ribs and the medial borders of the clavicles are symmetrical (Fig. 4.4). It is important to keep in mind that pneumothorax can present as a hyperlucent lung when the radiograph is obtained in a supine position and the air

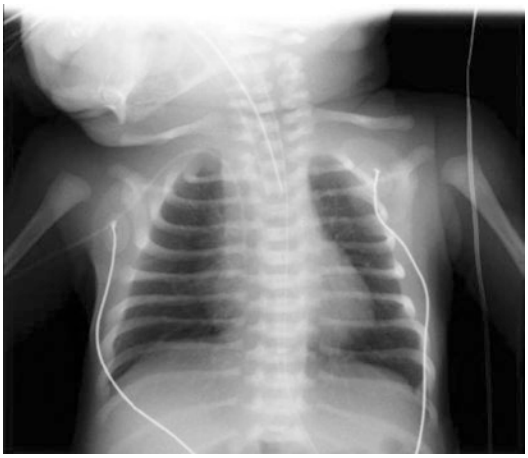

Fig. 4.1 Improper XR acquisition of the thorax in a toddler. Field of view should be centred on the thorax, a large thoraco-abdominal field of view is incorrect. Lordotic position shows horizontal pattern of the posterior ribs and diffuse opacity of basal right chest due to cardiac projection simulating right cardiac hypertrophy

M. B. Damasio (✉) · F. Rizzo · F. Sertorio · L. Anfigeno
Radiology Unit, IRCCS Giannina Gaslini,
Genoa, Italy
e-mail: beatricedamasio@gaslini.org;
francescarizzo@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_4

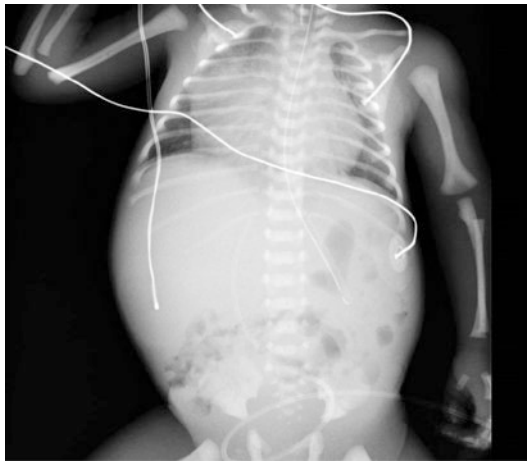

Fig. 4.2 XR acquired with caudocranial angulation of X-Ray tube: bizarre configuration of the ribs and gross distortion of the chest, simulating a bone dysplasia, with clavicles bilaterally projected superiorly to the chest apex

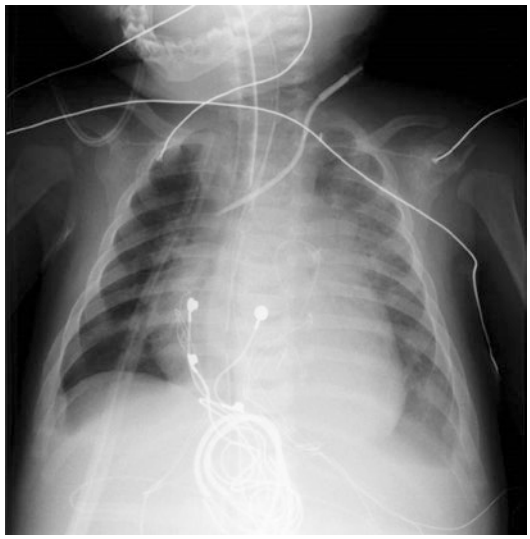

Fig. 4.3 XR acquired with rotated patient. Hyperlucency of one lung can be seen and should not be misinterpreted as a pathological finding

is located anterior to the lung. A lateral decubitus view should be performed to verify its presence (Fig. 4.5). Devices should be accurately displaced before image acquisition, otherwise, chest image could be misinterpreted (Fig. 4.6).

Young children are often unable to follow the operator's breathing instructions; therefore,

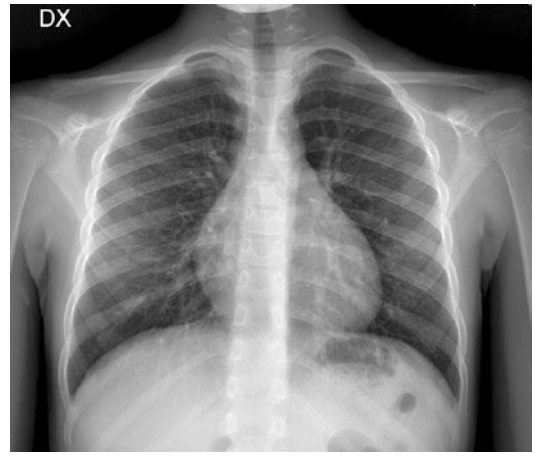

Fig. 4.4 XR correct projection shows symmetrical medial borders projection of clavicles

it is essential to assess the depth of inspiration before interpreting the images. The features seen on films obtained in expiration often simulate cardiomegaly or increased lung density, mimicking pulmonary disease [1–3]. Lateral buckling of the trachea at the thoracic inlet is a normal occurrence in infants and toddlers. The displacement is always on the opposite side from the aorta, and it is usually seen in expiratory films. Radiologists should also be aware that an excessively high kVp setting can obliterate the pulmonary vasculature, which is an important element for correct interpretation of cardiovascular disorders. The estimated median effective dose for a chest X-ray is about 0.01–0.02 mSv [4].

4.3 Ultrasound

Although plain X-ray still remains the initial modality for paediatric chest imaging, there has been a significant increase in the clinical utility of chest ultrasound in recent years. Improvement in transducer technology and colour flow imaging and widespread application of the ALARA principle have contributed to this trend. Ultrasound is economical, easily available, portable, and ionizing radiation free. It can be performed after careful evaluation of the chest radiograph.

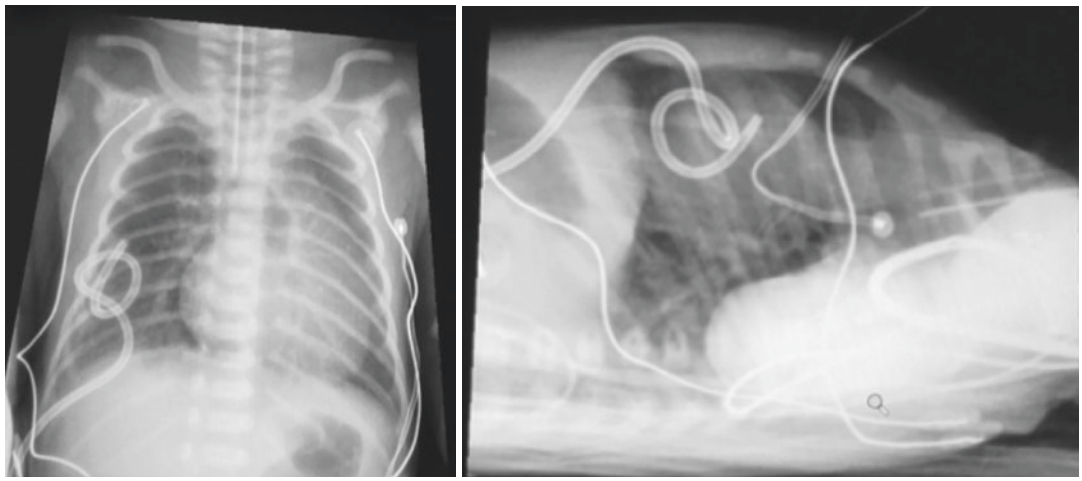

Fig. 4.5 XR acquired in AP and lateral decubitus. Pneumothorax can present as a hyperlucent lung when the radiograph is obtained in a supine position. The air is located anterior to the lung. A lateral decubitus view should be performed to verify its presence

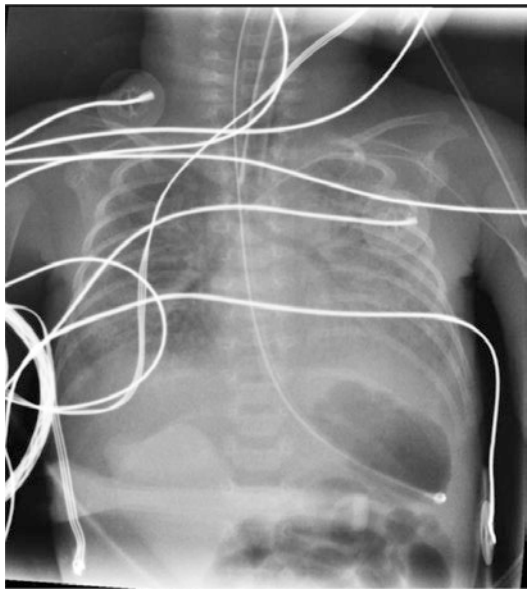

Fig. 4.6. XR of the thorax. Presence of multiple devices. A correct interpretation of imaging findings is not possible in case of multiple projections

Possible acoustic windows used for evaluating the chest with corresponding views are reported (see Fig. 4.7).

- Suprasternal notch (Fig. 4.7a).
- Parasternal region (Fig. 4.7b).
- Longitudinal emi-clavear line (Fig. 4.7c).
- Longitudinal posterior ascellar (Fig. 4.7d).
- Axial intercostal space (Fig. 4.7e).
- Oblique parasternal (Fig. 4.7f).

The main indications for lung US in children include [5–8]:

- Diaphragm motility.
- Chest wall study (rib and muscle agenesis).
- Postoperative pneumothorax diagnosis.
- Diagnosis of pleural effusion: simple and complex (Fig. 4.8a and b).
- Evaluation and follow-up of consolidation (Fig. 4.9).
- Follow-up and evaluation of antenatally detected lung abnormalities.
- Assessment of opaque hemithorax.
- Misleading chest X-rays findings to differentiate cystic from solid lesions.
- Evaluate palpable chest wall lesions.
- Clarification of inconclusive plain film findings.
- Evaluation of the neonatal lung – neonatal point of care ultrasound.
- Evaluation of mediastinal widening and ruling out a normal thymus as the cause.
- Evaluation of vascular anomalies.

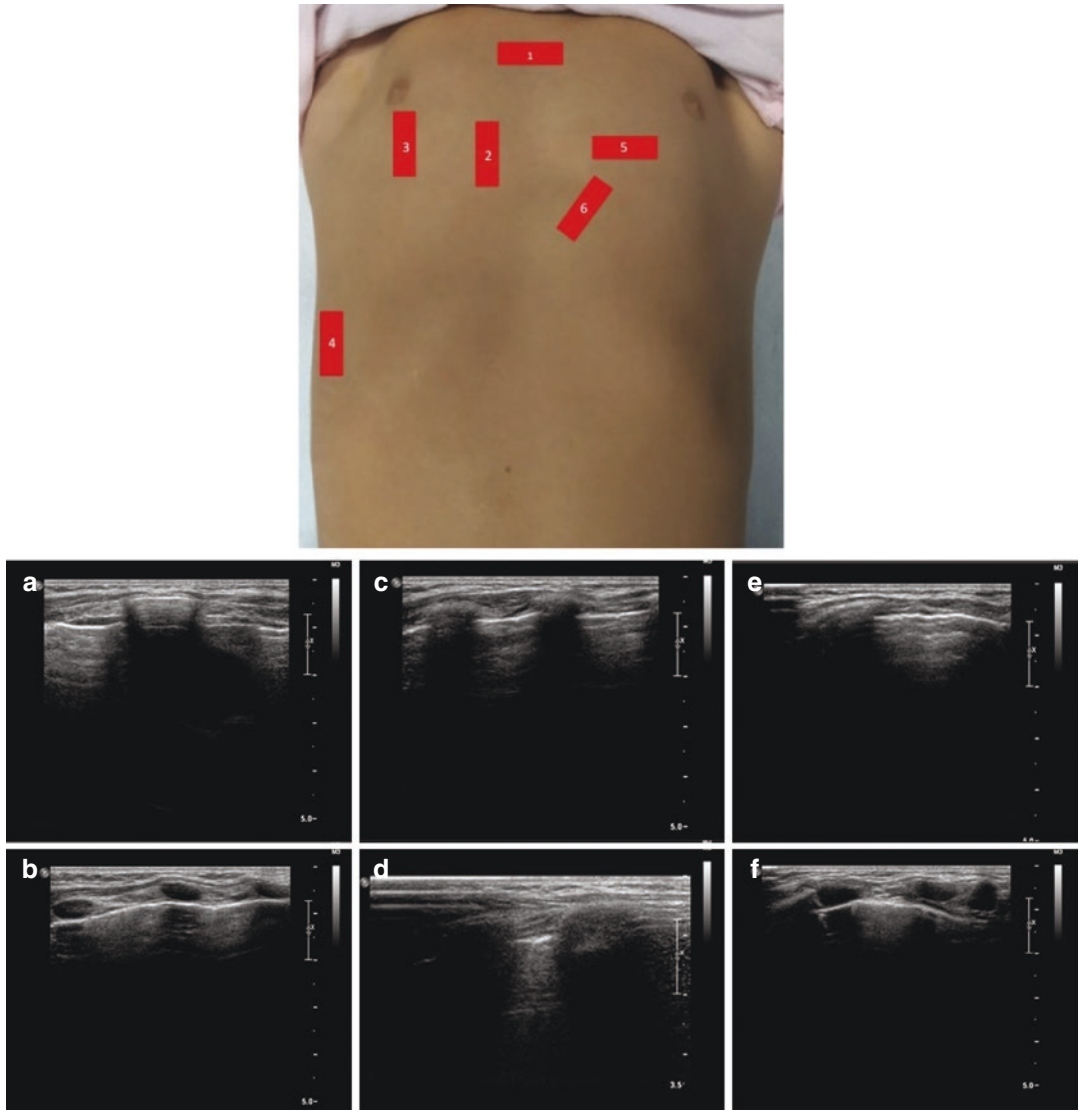

Fig. 4.7 Correct acoustic windows for B-Mode thoracic US: (**a**) suprasternal notch; (**b**) parasternal region; (**c**) longitudinal emiclavear line; (**d**) longitudinal posterior ascellar; (**e**) axial intercostal space; (**f**) oblique parasternal

- Search for lymph nodes.
- Assessing complications in patients with indwelling catheters.
- Assisting mediastinal biopsies.

The evaluation of the diaphragm, the subdiaphragmatic space as well as the liver and spleen should be part of the protocol as lung consolidation and empyema may be secondary to a liver abscess. The ribs in neonates and small infants have low mineral content, allowing trans-osseous scanning, especially in the parasternal region where the ribs are cartilaginous. This can be done through the transsternal and trans-costal approaches. A large thymus allows excellent visualization of the mediastinum as it provides an acoustic window for the ultrasound. A drawback in older children is the inability to obtain a panoramic view of the chest, since the bones are ossified and the acoustic window available is limited. The type and frequency of transducer used

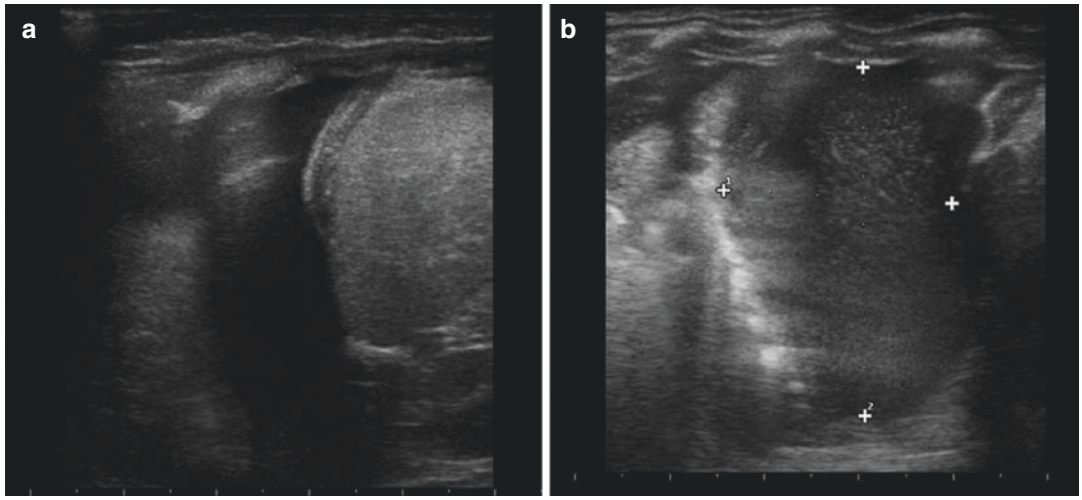

Fig. 4.8 B-Mode US shows simplex anechoic pleural effusion (**a**) and a 2.4 × 3.6 cm complex pleural effusion (**b**) with multiple hyperechogenic spots inside and compressive pulmonary atelectasis

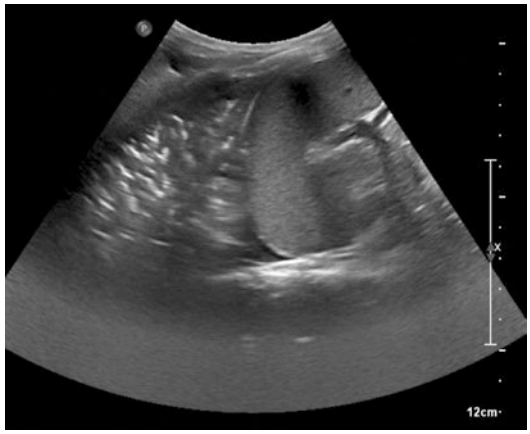

Fig. 4.9 B-Mode US shows pulmonary consolidation: in this case is possible to appreciate diffuse hyperechogenicity within lower airways typically seen in air bronchogram

would vary with the age of the patient and the location of the lesion. Linear transducers with high frequency and a small footprint are preferred to perform sagittal and intercostal scans in neonates.

Colour flow is useful to characterize the vascular pattern within the lesion. Contrast administration and sedation are not required. Moreover, chest US can support thoracentesis, thoracotomy and image-guided drainage.

4.4 Computed Tomography

CT allows the evaluation of interstitial lung diseases, congenital lung malformations and cardiovascular abnormalities, neoplasms (primary and secondary tumours) and traumatic lesions. Compared to radiography, CT requires a relatively high radiation dose and should be considered only after carefully weighing the potential risks and benefits. Each CT study must be clinically justified, and the ALARA principles (As Low as Reasonably Achievable) must be observed. Fortunately, over recent decades, technical innovations in CT scanner technology and image reconstruction have resulted in a substantial reduction of the radiation dose [9]. Powerful post-processing techniques, such as iterative image reconstruction, allowed reduction of the radiation dose to levels that are nowadays in the order of 3–6 months background radiation [9].

Furthermore, thanks to the development of very fast CT scanners, it is now possible to scan even rapidly breathing young children without the need for anaesthesia or sedation.

As a result of these innovations, chest CT can now be used more safely in paediatric population to diagnose and monitor a wide range of lung diseases.

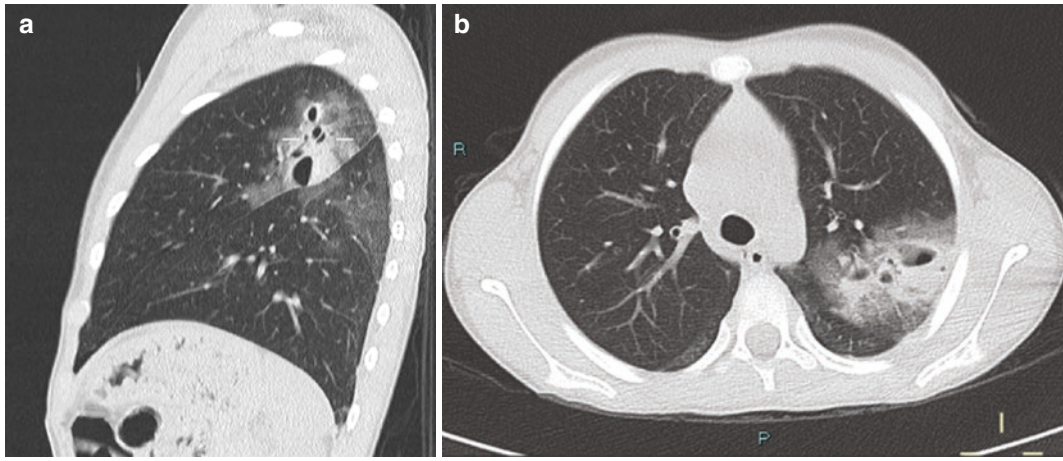

Fig. 4.10 HRCT sagittal (**a**) and axial (**b**) shows pulmonary left postero-apical para-scissural contusion area with presence of air in the context and peripheral ground glass

The main indications for lung CT in children include:

- Parenchymal lung diseases (Fig. 4.10a and b).
- Airway diseases (Fig. 4.11).
- Complicated consolidation (Fig. 4.12).
- Congenital lung malformations.
- Cardiovascular malformations.
- Assessment of an opaque hemithorax (Fig. 4.11).
- Tumour.
- Traumatic lesions (Fig. 4.10).
- Evaluation of central airway dynamics and dimensions (tracheo-broncomalacia).
- Chest wall evaluation for pectus Excavatum or carinatum, Poland syndrome.

Imaging of most congenital malformations requires contrast medium injection, especially if there is an abnormal vascular component. Contrast injection is also indicated in the case of tumour.

Iodinated contrast medium IS injected at a dose of 1–2 mL/kg according to iodine concentration.

The radiologist is responsible for ensuring that the exam protocol is customized for each individual patient. The final goal is to obtain the best imaging with the lowest exposure of the patient to the radiation burden. Multiplanar and 3D renderings further increase imaging usefulness.

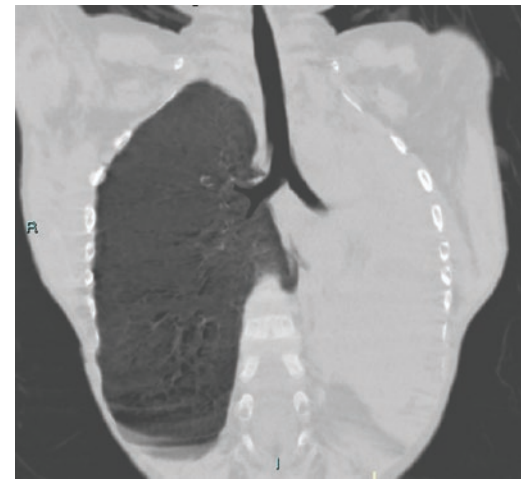

Fig. 4.11 HRCT: MinPR—lungs window shows diffuse and massive left pulmonary resorption atelectasis due to foreign body within principal left bronchus

To date, the implementation of CT protocols has been largely performed by local radiology communities and has been focused on the balance between diagnostic image quality and radiation dose levels [10].

The European guidelines (2018) for the diagnostic reference values for chest CT are reported in Table 4.1 [11].

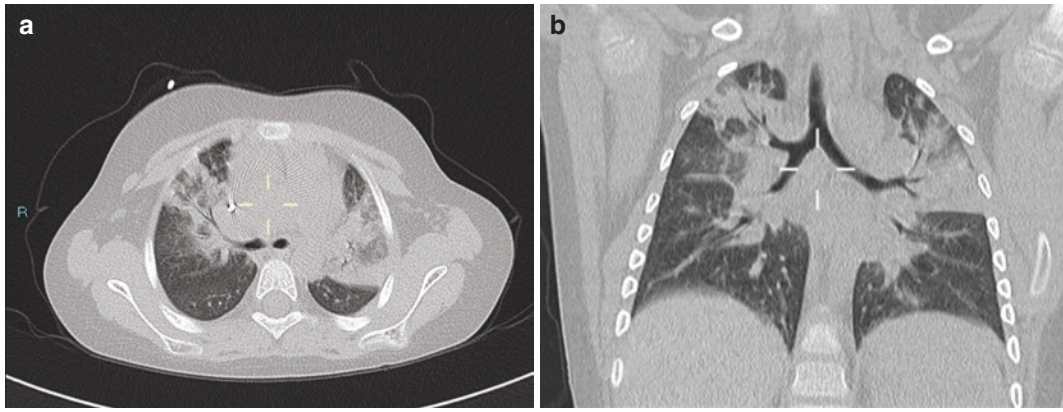

Fig. 4.12 HRCT (**a**) axial and (**b**) coronal planes shows bilateral pulmonary consolidation with air bronchogram in a febrile immunocompromised child with cough and expectoration

Table 4.1 European guidelines (2018) for the diagnostic reference values for chest CT [11]

Computed tomography			
Exam	Age or weight group	EDRL	
		$CTDI_{vol}$, mGy	DLP, mGy cm
Head	0-<3 months	24	300
	3 months-<1 y	28	385
	1-<6 y	40	505
	≥6 y	50	650
Thorax	<5 kg	1,4	35
	5-< 15 kg	1,8	50
	15-< 30 kg	2,7	70
	30-<50 kg	3,7	115
	50-<80 kg	5,4	200
Abdomen	<5 kg		45
	5-< 15 kg	3,5	120
	15-< 30 kg	5,4	150
	30-<50 kg	7,3	210
	50-<80 kg	13	480

CTDI Computed Tomography Dose Index; *DLP* Dose Length Product; *mGy* milligray

However, a multicentre survey on patient dose in paediatric imaging (2019) has recently proposed an update for diagnostic reference levels for France.

The reported DLP values (mGy.cm) are significantly lower, ranging from 15 to 38 for paediatric patients. This new survey contributes to the continuing optimization process in paediatric CT practice [12].

4.5 Magnetic Resonance Imaging

Although MRI has revolutionized medicine in many disease areas, its use for lung diseases became a clinical reality only in recent years. The reasons for this include the low-proton density of lung tissue, the continuous motion of the lung

and the elevated air content, which results in low signal intensity and fast signal decay. In 1983, the first studies which included chest MRIs in children were published [13, 14].

Major innovations in chest MRI in paediatrics have taken place over the past decade with fast acquisition techniques, respiratory and electrocardiographic gating and new high-resolution techniques.

Thanks to technological improvements the gap of image-quality between CT and MRI [14] is shortening.

The main indications for lung MR in children include:

- Evaluation of congenital lung masses, both during foetal age and in the post-natal follow-up (Fig. 4.13).
- Evaluation and follow-up of consolidations and infections.
- Search for metastatic nodules.
- Follow-up in cystic fibrosis (CF) (Fig. 4.14a and b).
- Chest wall evaluation for pectus Excavatum or carinatum, Poland syndrome.
- Dynamic evaluation of cardiac compression in pectus excavatum.

Many of the MRI innovations described above were initially developed for CF and are now also applied for research in asthma [15], immunocompromised children [16], pulmonary infections [17], tuberculosis [18], BPD [19, 20], congenital diaphragmatic hernia [21, 22] and pulmonary sarcoidosis [23].

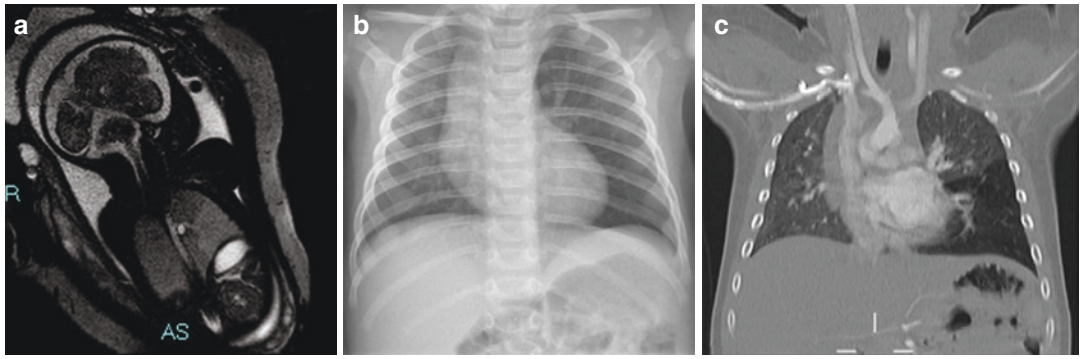

Fig. 4.13 (**a**) Fetal MR (BTFE coronal sequence) shows hyperintensity of the low and medium left parenchymal fields. XR at birth confirmed left inferior parenchymal hyperinflation (**b**); coronal MPR CT reconstruction confirmed the presence of focal hyperinflation secondary to congenital lobar enphisema

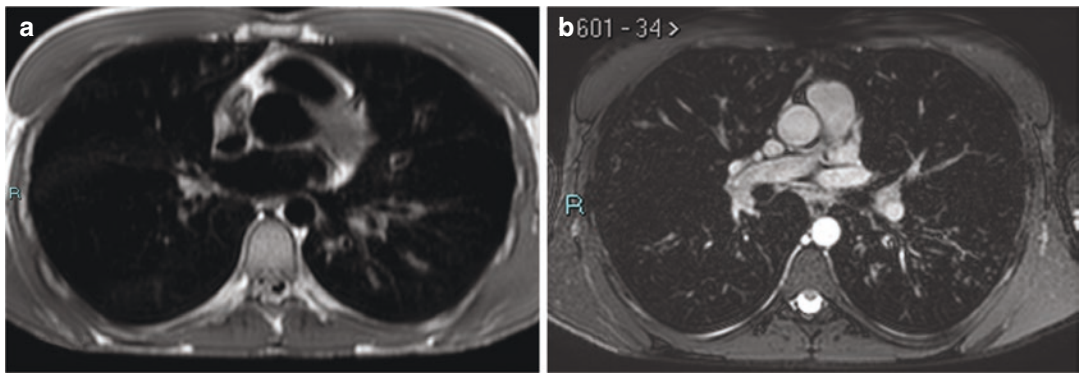

Fig. 4.14 MRI in a patient with CF; (**a**) axial Single Shot SPIR shows diffuse bilateral bronchiectasis with bronchial wall thickening (**b**) follow-up axial BTFE sequence shows a "tree in bud" pattern of the peripheral bronchial tree

Table 4.2 Protocol adopted in our Institute for FC assessment

Sequences	Voxel (mm)	Thickness (mm)	Number of excitations (NEX)	Triggering
Black Blood Single Shot (axial)	1.75 × 2.25	5/0	2	Free breath
DWI (axial)	2.5 × 2.5	5/1	5	Triggered
BTFE (axial)	1.9 × q.9	5/0.5	1	Breath hold
Black Blood Single Shot SPIR (axial)	1.75 × 2.25	5/0	2	Free breath

DWI Diffusion-Weighted Imaging; *BTFE* balanced turbo field echo; *SPIR* spectral pre-saturation with inversion recovery

Chest MRI is increasingly used for the assessment of central airway dynamics and dimensions [24]. Another important advantage of chest MRI over chest CT is that MRI allows the acquisition of simultaneous information on lung structure and function. This opens new ways to study lung mechanics in asthmatic subjects [25].

State-of-the art thoracic MRI now has the potential as a substitute for traditional imaging techniques and/or to play a complementary role in patient management also in pulmonary oncology [26].

Lung functional evaluation includes measurements of perfusion and blood flow, with or without contrast enhancement, ventilation, gas exchange, respiratory motion, and mechanics.

The major challenge for the MRI inclusion into the daily clinic is its protocols standardization across centres and vendors.

A fundamental MR imaging protocol evaluating the lung parenchyma includes:

- a gradient recalled echo (GRE) multiplanar localizer,
- coronal T2 single-shot half Fourier turbo spin echo (HASTE),
- axial 3-dimensional (3D) GRE T1,
- coronal balanced steady-state free precession (true fast imaging with steady-state precession),
- axial short tau inversion recovery.

This practical MR imaging examination in less than 25 min.

If necessary, postcontrast imaging with a 3D GRE T1-weighted sequence with fat saturation can provide information regarding enhancement characteristics.

Paediatric patients with difficulty after breathing instructions because of their young age or critical condition often benefit from a sequence that does not rely on breath holds such as an axial.

T2 periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER/BLADE) performed with the patient free breathing.

The protocol adopted in our Institute for FC assessment is reported in Table 4.2.

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Anesthesia in Thoracic Surgery

5

Giovanni Montobbio and Clelia Zanaboni

5.1 Introduction

In the pediatric population, thoracic surgery is performed to treat a great variety of pathologies, and it may be challenging for the anesthesiologist.

Children may present in varying age and weight and may present with different degrees of pulmonary compromise; so, it is mandatory for the anesthesiologist to understand the pediatric physiology as well as the principles of pediatric anesthesia and thoracic anesthesia in order to provide the best and safe care for these children [1, 2].

Video-assisted thoracoscopic surgery (VATS) is a less invasive approach for thoracoscopic surgery. It renders less postoperative pain, fewer operative complications, and shortened hospital stay. This makes VATS favorable for pediatric patients [3].

This chapter delineates anesthetic management of children submitted to thoracic surgery, the methods to obtain single lung ventilation (SLV), the difficulties encountered while surgery proceeds, and the management of special circumstances. Cardiac surgery is beyond the scope of this review.

The main aspects of the management of postoperative pain will be underlined.

G. Montobbio · C. Zanaboni (✉)
Anesthesiology and Therapy of Acute and Procedural Pain Unit, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: giovannimontobbio@gaslini.org; cleliazanaboni@gaslini.org

5.2 Preoperative Evaluation

Different management is required at different ages, and the wide spectrum of conditions and physiologic compensatory mechanisms involved demand each patient an individual and complete assessment.

Preoperative evaluation has the goal to gain information regarding the patient's current status, familiarity, key elements of the child's medical history, and coexisting congenital or acquired conditions such as cardiac diseases or bronchopulmonary dysplasia.

In particular, for younger patients, the medical history begins with the prenatal course and neonatal period because events during pregnancy and delivery may influence the child's current health status [4]. A complete review of systems should be included with emphasis placed on medical comorbidities that may influence either the choice or the outcome of anesthesia [5].

The older patients affected by the thoracic disease may present exercise intolerance, dyspnea, cyanosis, wheezing, coughing, and weight loss, while infants often show fewer specific signs such as poor feeding, irritability, or change in sleep habits [1].

During the visit, a complete and accurate physical examination must be performed; of course, all children undergoing thoracic surgery should have a complete examination of the airway in order to detect potential airway

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_5

management problems, upper respiratory tract infections, abnormal airway or extrinsic tracheal compression that may create difficult intubation, or issues in the placement of devices for SLV. All these findings could increase the anesthesia risks. The physical examination should seek to discover signs of cardiac compromise, such as irritability, rales, cyanosis, jugular venous distention, and hepatomegaly, as a consequence of the primitive disease on the cardiocirculatory system.

Laboratory investigations should be selected regarding the presenting disease and the procedure being performed. A complete blood count (CBC) should be obtained preoperatively and, since blood transfusion may be necessary, the preoperative assessment should include blood type, antibody screen, and blood crossmatch. A chest X-ray is always necessary for those children who are prone to be submitted to the thoracic procedure which the anesthesiologist must evaluate for pulmonary and mediastinal findings, scoliosis, deviation of the trachea, engorgement of the vascular structures, and abnormal cardiac profile.

A CT scan is needed in almost all cases scheduled for surgery; it helps to evaluate the pulmonary parenchyma and its anomalies; to detect the position and the extent of mediastinal masses and their relationships with the surrounding structures such as hearth, great vessels, trachea, and bronchi; to evaluate the position and diameter of the trachea, and to study the abnormalities of the chest.

Patients undergoing thoracic surgery, in particular the youngest and those most affected, are frequently unable to adequately perform preoperative pulmonary functional tests (PPFT). Moreover, as demonstrated by Yuan [6] and Burjek [7], in patients undergoing spinal fusion, there is no association between results, postoperative prolonged intubation, and intensive care unit admission. For these reasons, PPFT are not routinely used for preoperative assessment in a patient scheduled for thoracic surgery.

An ECG and transthoracic echocardiography are needed to evaluate the cardiac anatomy and function in patients with symptoms of hemodynamic compromise.

Moreover, during the preoperative visit begins the relationship among the anesthesiologist, the child, and his family; the anesthetic plan and its risk should be outlined such as the options for postoperative analgesia and the postoperative disposition.

5.3 Intraoperative Management

An inhalation anesthetic agent (sevoflurane) or, if an intravenous (IV) line is present, propofol or midazolam may be used for induction of anesthesia. Opioids (fentanyl and remifentanyl) and neuromuscular blocking drugs (rocuronium and cisatracurium) are administrated to reach a good anesthesia level and to facilitate endotracheal intubation. For open thoracotomies in neonates and infants, SLV is not generally needed because the surgeon is usually able to manually retract the lung. Thoracoscopic procedures may require SLV to improve visualization and reduce the risk of injury of the lung and adjacent structures. If needed the SLV will be established (see later) and mechanical ventilation started with a fraction of inspired oxygen (FiO_2) and tidal volume calibrated on peripheral capillary oxygen saturation (SpO_2) and the amount of carbon dioxide in exhaled air ($EtCO_2$).

For maintenance of anesthesia, there are many options: sevoflurane or propofol plus remifentanil by continuous infusion. The author's choice is sevoflurane plus remifentanil for children under 12 years of age and propofol in target-controlled infusion (TCI) plus remifentanil for adolescents. In neonates, propofol is contraindicated and sevoflurane may precipitate hypotension, especially in those with poor cardiac function or hypovolemic so the association midazolam/remifentanil by continuous infusion is generally preferred.

Regarding the possibility that inhalation anesthesia may impair hypoxic pulmonary vasoconstriction (HPV) and may increase intrapulmonary shunt and hypoxemia, no evidence indicates that the drug used to maintain anesthesia (intravenous versus inhalational) during SLV may affect patient outcomes [8]. A thoracic epidural catheter

may be beneficial in thoracotomy or thoracoscopic procedures when thoracostomy tube drainage is placed following surgery.

To carefully monitor arterial blood pressure and arterial blood gases during intraoperative lung manipulations and SLV, arterial catheterization is strongly recommended. It should be considered mandatory in patients undergoing thoracotomy, neonates, and those with severe lung disease undergoing thoracoscopic surgery. It may be avoided for short thoracoscopic procedures in patents without severe lung diseases. If extensive blood loss is expected or if the patient is already critical, a central venous catheter is recommended to administrate catecholamines and to monitor central venous pressure.

Temperature monitoring is mandatory in neonates and infants and children undergoing long procedures; a bladder catheter with a temperature probe allows central temperature and urine output monitoring.

5.4 Single Lung Ventilation (SLV) During Pediatric Thoracic Surgery

5.4.1 Ventilation and Perfusion During Thoracic Surgery: Adults versus Children

Ventilation and perfusion (V/Q) are highest on the most dependent portion of the lungs for adults and children due to pressure gradient and gravitational pull. Both factors (V and Q) should be well matched. However, during SLV IN VATS, there are factors that can increase V/Q mismatch because of a decrease in functional residual capacity and tidal volume. General anesthesia, suboptimal patient positioning, surgical retraction, and mechanical ventilation contribute to V/Q mismatch [9]. HPV minimizes V/Q mismatch by diverting blood flow away from the atelectatic under-ventilated lung. The HPV response is maximal at normal and decreased at either high or low pulmonary vascular pressure [10].

Furthermore, one can attain maximal HPV when partial pressure in venous blood (PvO_2) is normal and with a decreased response when either high or low PvO_2. Therefore, the use of inhalational anesthetic agents and other vasodilating drugs, together with high or low FiO_2, will diminish HPV response [11]. This principle holds true for children and young adults [12].

The impact of lateral decubitus position on V/Q mismatch on the other hand is different in infants when compared to teens and adults. In adults with unilateral lung disease, oxygenation is optimal when the patient is placed in the lateral decubitus position with the healthy lung dependent (“down”) and the diseased lung nondependent (“up”) because ventilation is normally distributed preferentially to dependent regions of the lung so that there is a gradient of increasing ventilation from the most nondependent to the most dependent lung segments [13, 14].

Presumably, this is related to an increase in blood flow to the dependent, healthy lung and a decrease in blood flow to the nondependent, diseased lung because of the hydrostatic pressure (or gravitational) gradient between the two lungs. This phenomenon promotes V/Q matching in the adult patient undergoing thoracic surgery in the lateral decubitus position.

In infants with unilateral lung disease, oxygenation is improved with the healthy lung “up” [15]. Several factors account for this discrepancy between adults and infants. Infants have a soft, easily compressible rib cage that cannot fully support the underlying lung. Functional residual capacity, therefore, is closer to residual volume, making airway closure likely to occur in the dependent lung even during tidal breathing [16]. When the adult is placed in the lateral decubitus position, the dependent diaphragm has a mechanical advantage because it is “loaded” by the abdominal hydrostatic pressure gradient. This pressure gradient is reduced in infants, reducing the functional advantage of the dependent diaphragm. The infant’s small size also results in a reduced hydrostatic pressure gradient between the nondependent and dependent lungs. Consequently, the favorable increase in perfusion to the dependent, ventilated lung is reduced in infants. Thereby, during thoracic surgery, several factors interact to affect the ventilation/perfusion

(V/Q) balance. Compression of the dependent lung in the lateral decubitus position and SLV with the collapse of the operative lung are both responsible for atelectasis. Hypoxic pulmonary vasoconstriction acts to divert blood flow away from underventilated lung regions, thereby minimizing any V/Q imbalance. However, the overall effect of the lateral decubitus position on the V/Q balance is different in infants compared to older children and adults.

Finally, the infant's increased oxygen requirement, coupled with a small functional residual capacity, predisposes to hypoxemia. Infants normally consume 8–10 mL of oxygen kg/min compared to normal oxygen consumption in adults of 2–3 mL/kg/min [17]. For these reasons, infants are at increased risks of significant oxygen desaturation during surgery in the lateral decubitus position.

5.4.2 Indications and Techniques for SLV in Infants and Children

It has been long established that there are differences between the pediatric and adult airways that are well known to the anesthesiologist. Of all the airway differences, it is the smaller size of the pediatric airway that necessitates the need for a range of airway devices to provide SLV. The preferred method of lung isolation in the adult population, a double-lumen tube (DLT), cannot be used in infants and small children because of the smaller airway size.

The anesthesiologist must have proficient knowledge of tracheobronchial anatomy in order to optimally place lung isolation devices and troubleshoot problems using fiberoptic bronchoscopy. Prior to 1995, nearly all thoracic surgery in children was performed by thoracotomy. In the majority of cases, anesthesiologists ventilated both lungs with a conventional tracheal tube, and the surgeons retracted the operative lung to gain exposure to the surgical field. During the past decade, the use of video-assisted thoracoscopic surgery (VATS) has dramatically increased in both adults and children. Reported advantages of thoracoscopy include smaller chest incisions, reduced postoperative pain, and more rapid postoperative recovery compared to thoracotomy [18–20]. Video-assisted thoracoscopic surgery is being used extensively for pleural debridement in patients with empyema, lung biopsy, and wedge resections for interstitial lung disease, mediastinal masses, and metastatic lesions. More extensive pulmonary resections, including segmentectomy and lobectomy, have been performed for lung abscesses, bullous disease, sequestrations, lobar emphysema, cystic adenomatous malformations (CPAM), and neoplasms. In select centers, more advanced procedures have been reported, including the closure of patent ductus arteriosus, repair of hiatal hernias, and anterior spinal fusion. VATS can be performed while both lungs are being ventilated using carbon dioxide insufflation and placement of a retractor to displace lung tissue in the operative field. SLV is extremely desirable during VATS, however, because lung deflation improves visualization of thoracic contents and may reduce lung injury caused by the use of retractors [21]. Several techniques can be used for SLV in children.

5.4.3 ABCDs of Pediatric Lung Isolation

Slinger teaches that there are the "ABCs" of adult lung isolation: anatomy, bronchoscopy, and chest imaging [21]. In pediatric lung isolation, there are still all the same "ABC" considerations, with the addition of "D" the varying diameters of the pediatric airway with age [22].

A = Anatomy

It has been long established that there are differences between the pediatric and the adult airways that are well known to the anesthesiologist. Of all the airway differences, it is the smaller size of the pediatric airway that necessitates the need for a range of airway devices to provide SLV. The anesthesiologist must have proficient knowledge of tracheobronchial anatomy in order to optimally place lung isolation devices and troubleshoot problems using fiberoptic bronchoscopy.

B = Bronchoscopy

When choosing a bronchoscope to be placed within an endotracheal tube (ETT), there are two questions to ask: (1) What size bronchoscope can I use that will physically fit and(2) What size bronchoscope can I use and still ventilate the patient [22].

Bronchoscopes come in varying sizes. Bronchoscopes are labeled by the outside diameter (OD) of the scope. The sizing of various types of TTs is done differently depending on the type. A single-lumen tracheal tube (SLT) is labeled by the inside diameter (ID) of the respiration lumen. A double-lumen TT is labeled by the OD of the entire tube, with the measurement reported in French (Fr). For a well-lubricated bronchoscope to physically fit inside the lumen of the TT (and not seize up from friction), the OD of the bronchoscope (OD_B) needs to be <90% of the ID of the TT (ID_{TT}).

In order to allow some ventilation during the time of bronchoscopy, the cross-sectional area of the bronchoscope (CSA_B) cannot take up more than 50% of the cross-sectional area of the TT lumen. The smallest fiberoptic scope in general use is the Olympus BF N20, with an OD of 2.2 mm [22].

It is always a good idea to test the fit of the bronchoscope inside a TT before use in the patient.

C = Chest imaging

As part of the preoperative assessment of the patient, the anesthesiologist should always look at all available chest imaging, X-ray, or computed tomography (CT). These may reveal issues with lung isolation such as a narrowed distal trachea, or a compressed bronchus.

CT scans can also be used to assist in choosing an appropriate TT size.

D = Diameter of the pediatric airway

The average neonatal trachea has an anteroposterior diameter of about 4.3 mm for both males and females [23].

The trachea grows uniformly in males and females to about 14 mm at the age of 15 years. At this time, the female trachea stops growing. However, the male trachea continues to grow to 16–18 mm by the age of 19. The trachea is the shape of an ellipse, with the transverse diameter being larger than the anteroposterior diameter [24, 25]. The sizing of airway devices should be based on the smaller (antero-posterior) diameter.

5.4.4 Options for Lung Isolation

Frequently, infants undergoing thoracotomy do not require lung isolation. Both lungs are ventilated, and the surgeon retracts and/or packs the operative lung as needed for operative exposure increasingly; however, SLV is being requested by surgeons, especially with the advances in technology that have permitted the use of video-assisted thoracoscopic surgery in infants and small children [26].

For the surgeon, there are several advantages to using SLV. The operative lung remains deflated and calm, thereby optimizing surgical exposure and enabling adequate "working space" in a relatively small anatomic compartment. This is particularly helpful when space-occupying lesions of the thorax are present, such as congenital cystic adenomatoid malformation (CPAM), pulmonary sequestration, and bronchogenic cyst. In cases of congenital lobar emphysema, SLV can help to minimize overdistension of the pathologic lobe [3]. Lung isolation will also facilitate demarcation of normal from abnormal lung in cases where incomplete fissures between the lobes make this differentiation difficult. From a mechanical standpoint, lung isolation prevents blood and secretions from the ipsilateral lung from migrating into the trachea and contralateral lung [27]. One obstacle to good surgical exposure in pediatric patients is providing consistent, SLV with relative ease, and reliability.

Techniques for SLV in children have included the use of double-lumen endobronchial tubes (DLTs) or Univent tubes, endobronchial intubation with a standard tracheal tube, use of a Fogarty catheter as a bronchial blocker, collapse of the surgical lung by insufflation of carbon dioxide, or lung retraction. These options all have their individual limitations, and none is entirely satisfactory [28, 29]. The challenge to the anesthesiologist is to choose a safe and effective means for isolating the lungs in each individual

patient. Using the patient's age and airway measurements allows the selection of the appropriate technique and tube. Individual patient characteristics must also be considered.

Guidelines for selecting appropriate tubes (or catheters) for SLV in children are shown in Table 5.1. There are significant variabilities in overall size and airway dimensions in children, particularly in teenagers. The recommendations shown in Table 1 are based on average values for airway dimensions. Larger DLTs may be safely used in large teenagers.

5.4.4.1 Single-Lumen Endotracheal Tube

Single-lumen ETT provides the simplest means of lung isolation. Tube size selection and depth of insertion follow the standard computation based on age; supported by auscultation for breath sounds.

After tracheal intubation, the ETT can deliberately be advanced into the bronchus to isolate the lungs. Difficulties arise when the left bronchus has to be intubated. In order to achieve blind left bronchial intubation, suggested techniques are using a stylet to curve the distal end of the tracheal tube to the left, and using a distally curved rubber bougie that is directed blindly to the left bronchus, followed by railroading the tube over the bougie [30]. Another technique for left lung intubation is when the level of the tube is rotated 180° while the head is turned to the right. The ETT is advanced into the bronchus until the right breath sound disappears [31]. The abovementioned techniques do not require a more advanced equipment unless there is a need to confirm tube placement with fiberoptic bronchoscopy (FOB). Single-lumen ETT is preferred for emergencies such as contralateral tension pneumothorax [32]. One of the challenges in using a single-lumen ETT is the inadequacy to provide a good seal in the bronchus. As a result, it may not be able to provide a collapsed lung for the operative site or protect the normal lungs from contamination [33].

5.4.4.2 Univent Tube

The Univent tube (Fuji Systems, Tokyo, Japan) is a conventional ETT with a second lumen containing a small tube that can be advanced into a bronchus [34–36].

Table 5.1 Tube selection for single-lung ventilation in children

Age (years)	ETT (ID)	BB (Fr)	Univent (ID)	DLT (Fr)
0.5–1	3.5–4.0	2–3		
1–2	4.0–4.5	3		
2–4	4.5–5.0	5		
4–6	5.0–5.5	5		
6–8	5.5–6	5	3.5	
8–10	6.0 cuffed	5	3.5	26
10–12	6.5 cuffed	5	4.5	26–28
12–14	6.5–7.0 cuffed	7	4.5	32
14–16	7.0 cuffed	7	6.0	35
16–18	8.0–8.5 cuffed	7–9	7.0	35

ETT, endotracheal tube; ID, internal diameter in mm; BB, balloon-tipped bronchial blocker; Fr, French; DLT, double lumen tube.

Table 1. 26 Fr—Rusch, Duluth, GA; 28–35 Fr—Mallinckrodt Medical Inc., St. Louis, MO
ID internal diameter, *Fr* French size, *DLT* double-lumen tube
Reproduced from: Hammer GB, Fitzmaurice BG, Brodsky JB: Methods for single-lung ventilation in pediatric patients. AnesthAnalg 89:1426–1429, 1999; with permission

A balloon located at the distal end of this small tube serves as a blocker. Univent tubes require a FOB for successful placement. Univent tubes are available in sizes as small as a 3.5 and 4.5 mm ID for use in children over 6 years of age [37]. Because the blocker tube is firmly attached to the main ETT, displacement of the Univent blocker balloon is less likely than when other blocker techniques are used. The blocker tube has a small lumen that allows egress of gas and can be used to insufflate oxygen or suction the operated lung.

The main disadvantage of Univent tubes is that the cross-sectional diameter of the ventilation lumen is smaller in order to accommodate the blocker lumen. This increases airway resistance also limits the size of the fiberoptic bronchoscope that may be used to facilitate positioning [38]. The Univent tube's blocker balloon has low-volume, high-pressure characteristics, so mucosal injuries can occur during normal inflation [39–41]. It is important to remember that the size of a Univent TT refers to the ID, where the OD will be much larger than the equivalent sized SLT. There is only a narrow age range, where the Univent tube is the preferred method for pediatric lung isolation. The Univent TT is not suitable under the age of 6, whereas DLT is the preferred method for patients older than 8 years.

5.4.4.3 Bronchial Blockers

Balloon-tipped bronchial blockers (BB) remain the "technique of choice" in pediatric patients under the age of 6 years [11]. This is because Univent 3.5 uncuffed version tube (recommended for 6–8 years old) and double-lumen EBT (recommended for 8–10 years old) diameters are big for the before mentioned age-group [8]. A variety of balloon-tipped catheters have been used for single lung ventilation, including an Arrow balloon wedge catheter (1) (Arrow International, Inc., Reading, PA), a Cook pediatric bronchial blocker (2) (Arndt blocker, Cook Medical, Inc., Bloomington, IN), and a Fogarty embolectomy catheter (Edwards Lifesciences Corp, Irvine, CA) (3).

Arndt pediatric endobronchial blocker (Cook Critical Care, Bloomington, IN, USA) is a Food and Drug Administration-approved device used to facilitate one-lung ventilation in children and adults. The smallest diameter endobronchial blocker currently manufactured is 5 Fr and can be inserted through an endotracheal tube with an internal diameter of 4.5 mm or greater.

The bronchial blocker is passed through a specialized adapter that is placed at the proximal end of the tracheal tube. This adapter contains the following four ports (Figs. 5.1 and 5.2):

- a connection to the tracheal tube
- a standard 15-mm adaptor for the anesthesia circuit
- a port for the bronchial blocker with a self-sealing diaphragm that can be tightened around the bronchial blocker to hold it in place, and a port for the flexible bronchoscope.

The bronchoscope is passed through its port and then through the wire loop at the end of the bronchial blocker. The bronchoscope and bronchial blocker are then passed under direct vision as a single unit into the main bronchus of the

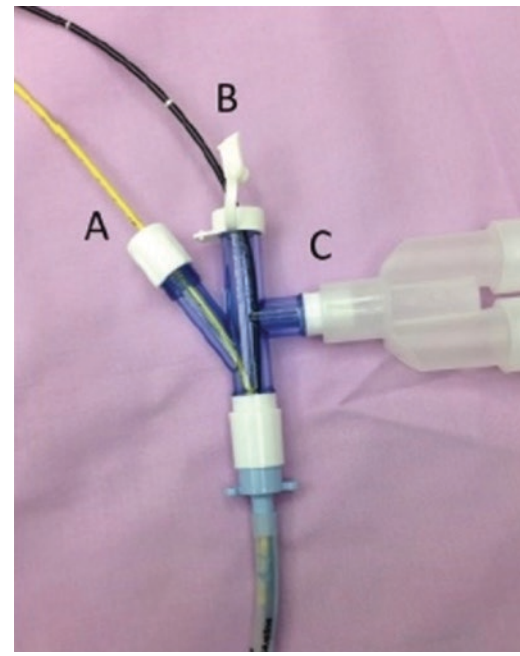

Fig. 5.1 Arndt endobronchial blocker® by Cook, Multiport airway adapter: (**a**) Blocker port, (**b**) FOB port, (**c**) Ventilation port

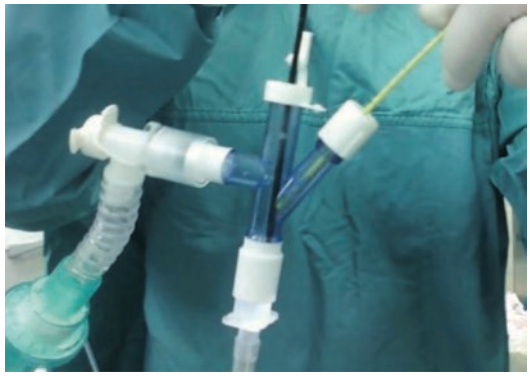

Fig. 5.2 Arndt endobronchial blocker kit

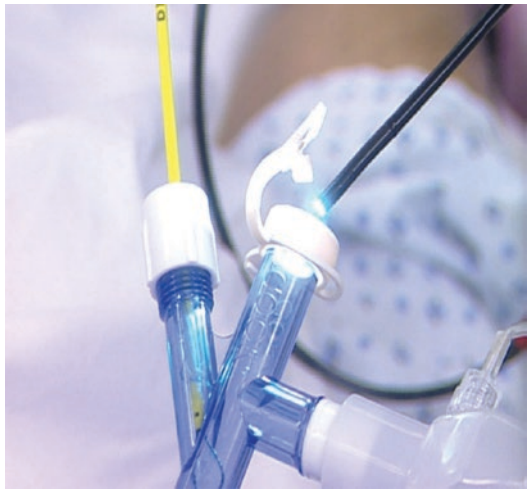

Fig. 5.3 Arndt endobronchial blocker® wire loop is coupled with FOB to direct the blocker to the mainstem bronchus

operative side (Figs. 5.3, 5.4, and 5.5), and the balloon is inflated under direct visualization (Fig. 5.6). When correct placement has been confirmed, the wire loop is removed from the central channel.

The Arndt blocker has a 2-mL cuff and lower inflation pressures and an inner lumen that contains a flexible nylon wire that extends along the length of the catheter and terminates as a flexible loop. This loop slides over the bronchoscope and aids in positioning. It is important to note that once the nylon guide is removed, it cannot be reattached, which may make repositioning attempts difficult should the blocker fall out of place. In the first generation of this device, it was

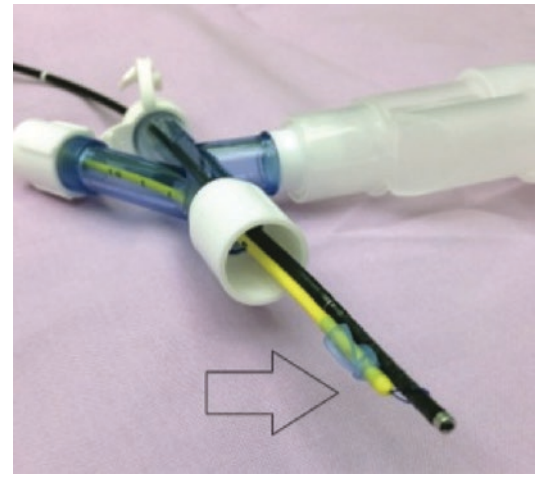

Fig. 5.4 Arndt endobronchial blocker® wire loop is coupled with FOB to direct the blocker to the mainstem bronchus

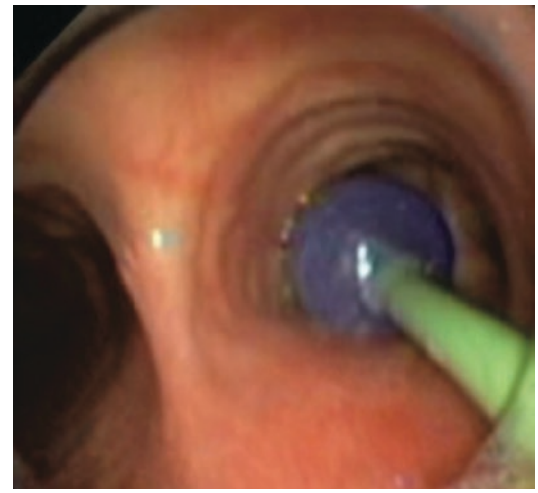

Fig. 5.5 Display the proper placement of a BB with the balloon fully inflated in the right mainstem bronchus

not possible to reinsert the string after it had been pulled out, losing the ability to redirect the bronchial blocker if necessary. Once the nylon wire is removed, the central lumen may be used for suctioning and to apply continuous positive airway pressure (CPAP).

The risk of hypoxemia during blocker placement is diminished, and repositioning of the blocker may be performed with fiberoptic guidance during surgery. Even with the use of a FOB with a diameter of 2.2 mm, however, the indwell-

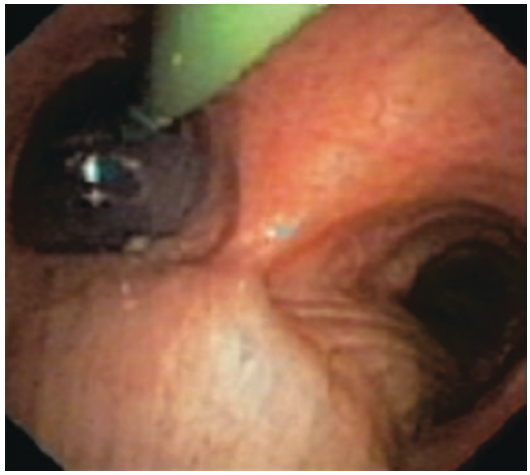

Fig. 5.6 Display the proper placement of a BB with the balloon fully inflated in the left bronchus

ing ETT must be at least 5 mm internal diameter (ID) to allow passage of the catheter and FOB. The use of this technique, therefore, is generally limited to children between the age of 18 months and 2 years

When a bronchial blocker is placed alongside the ETT, it can be placed directly into the bronchus on the operative side using direct laryngoscopy followed by fiberoptic guidance.

Alternatively, the mainstem bronchus on the operative site can be intubated, the bronchial blocker can be passed through the ETT, the ETT is then withdrawn, and the trachea reintubated so that the bronchial blocker lies on the outside of the ETT. Personal preference is to perform direct laryngoscopy and place the bronchial blocker through the glottic opening into the tracheal lumen followed by tracheal intubation with the ETT.

The OD necessitates a large SLT (at least 8.0 mm) to accommodate the bronchial blocker. Because the smallest lumen through which the pediatric endobronchial blocker can be inserted is an endotracheal tube with a 4.5mm internal diameter, it cannot be placed from within an endotracheal tube of a size appropriate for infants the size of our patient. However, as we have described herein, the pediatric endobronchial blocker can be effectively utilized in a small infant when attached to the outside of an appropriately sized endotracheal tube and positioned with the assistance of a fibroscope (Fig. 5.7).

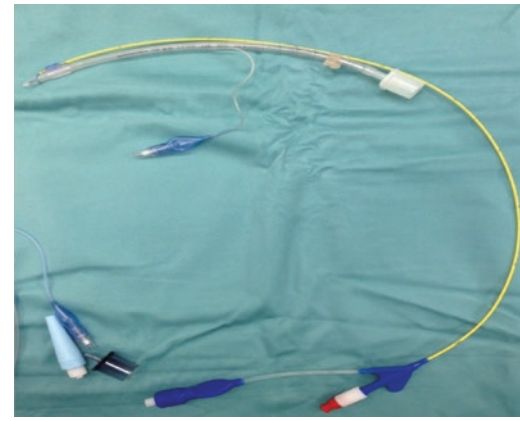

Fig. 5.7 Arndt blocker 5 French positioned outside the tube B

Given the outside diameter of the bronchial blocker and the inside diameter of the ETT in neonates, the bronchial blocker must be placed outside the ETT.

The degree to which this occurs depends on the outside diameter of the bronchial blocker and the inner diameter of the ETT. In the neonatal population, the bronchial blocker will obscure a significant percentage of the cross-sectional area of the ETT, thereby impairing ventilation. Correct placement will be guided by bronchoscopic visualization and it is not feasible, even when using ultrathin neonatal scopes, to pass both the bronchial blocker and the bronchoscope through the ETT [41].

The use of a bronchial blocker also eliminates the need to change a DLT to an SLT at the conclusion of the procedure. This is important because the airway at the conclusion of the procedure may be different from that in the initial period due to secretions and edema.

The main advantage of these blockers is that they can be placed through a conventional SLT. When a blocker is placed in the right main bronchus, it usually is positioned close to the carina to block the right upper lobe. Because the blocker balloon requires a high distending pressure, it easily slips out of the bronchus into the trachea because of changes in position or surgical manipulation. That movement can result in

Table 5.2 Arndt endobronchial blocker characteristics and guidelines

Arndt size (Fr)	External diameter (mm) cuff down	Best patient age (years)	Smallest ETT size (mm) for placement within ETT	Cuff inflation volumes (mL)	Fiberoptic bronchoscope (mm)
5.0	1.7	<8	4.5	0.5–2	2.2 or 2.8
7.0	2.3	8–12	6.5	2–6	2.8
9.0	3.0	>12	8	Spherical: 4–8 Elliptical: 6–12	2.8

obstructing ventilation and losing the seal between the two lungs (Table 5.2).

Fogarty embolectomy catheter or an end-hole, balloon wedge catheter may be used for the bronchial blockade to provide SLV [42–45]. The more commonly used Fogarty catheters come in a variety of sizes [39]. All but the smallest 2 and 3 Fr catheters have a removable guidewire that allows the user to angle the tip and direct the catheter into the desired bronchus to be isolated. The catheters may be placed either within or external to the TT. Positioning of the catheter is facilitated with a fiberoptic bronchoscope before balloon tip inflation. Because the Fogarty catheter has a low-volume, high-pressure balloon, it is imperative that a fiberoptic bronchoscope is used to observe the position and inflation of the balloon catheter to avoid damaging bronchial mucosa [46].

Placement of a Fogarty catheter is facilitated by bending the tip of its stylet toward the bronchus on the operative side. A fiberoptic bronchoscope may be used to reposition the catheter and confirm appropriate placement. When an end-hole catheter is placed outside the ETT, the bronchus on the operative side is initially intubated with an ETT. A guidewire is then advanced into that bronchus through the ETT. The ETT is removed, and the blocker is advanced over the guidewire into the bronchus. An ETT is then reinserted into the trachea along the blocker catheter. The catheter balloon is positioned in the proximal main stem bronchus under fiberoptic visual guidance. With an inflated balloon blocker, the airway is completely sealed, providing more predictable lung collapse and better operating conditions than with an ETT in the bronchus. There is no central channel for deflation or CPAP to the operative lung. Deflation of the operative lung occurs by absorption atelectasis and requires a considerably longer period of time.

A potential problem with this technique is the dislodgement of the blocker balloon into the trachea. The inflated balloon will then block ventilation to both lungs or prevent the collapse of the operative lung. The balloons of most catheters used for bronchial blockade have low-volume, high-pressure properties, and overdistention can damage or even rupture the airway. A recent study, however, reported that bronchial blocker cuffs produced lower "cuff-to-tracheal" pressures than double-lumen tubes (DLTs) [47].

When closed-tip bronchial blockers are used, the operative lung cannot be suctioned and CPAP cannot be provided to the operative lung if needed. Recently, adapters have been used to facilitate ventilation during the placement of a bronchial blocker through an indwelling ETT [48].

5.4.4.4 Double-Lumen Tubes (DLTs)

Often considered the gold standard for lung isolation, the double-lumen endobronchial blocker or DLT is suitable for children older than 8 years of age [49]. The DLT is composed of two lumens fused in parallel with one lumen that is angled and longer than the other and meant to be inserted into the desired bronchus, while the shorter lumen remains in the trachea. Both lumens are cuffed such that single-lung ventilation and double-lung ventilation may be easily achieved by clamping and releasing the appropriate limb on the adapter piece. Marraro [49] described a bilumen tube for infants. The inflated bronchial cuff allows ventilation to be diverted to either or both lungs and protects each lung from contamination from the contralateral side.

The equation of Size = Age × 1.5 + 14 can help to estimate the sizing needed. The smallest DLT size is a 26 Fr, which is generally suitable for children 8–10 years of age. One study sug-

gested that the use of the 26 Fr DLT may be considered for children as young as 8 years and as small as 30 kg of weight and 130 cm of height. They should meet at least two of these parameters [50]. DLTs are available in left or right-sided tubes, although the left-sided tube is more commonly used as it avoids potentially obstructing the right upper lobe bronchus. Double-lumen tubes are inserted in children using the same technique as in adults [51].

Insertion is performed by direct laryngoscopy, or in the case of a difficult airway, a fiberoptic scope or tube exchanger may be used. Once the bronchial tip is past the vocal cords, the preformed stylet is removed and the tube rotated 90° towards the desired bronchus [52]. The adapter piece is then connected and tracheal cuff inflated and connected to the ventilator. Fiberoptic bronchoscopy is recommended to confirm placement. When inflated, the bronchial cuff should still be seen within the bronchus, but the majority of the cuff should be within the bronchus to avoid dislodgement during surgery. If a bronchoscope is unavailable, placement may be confirmed by auscultation of the lungs after occlusion of ventilation to the desired lung and verifying the absence of breath sounds.

Advantages of a DLT include the ability to quickly alternate from single-lung ventilation to double-lung ventilation, ease of insertion, application of CPAP, and suctioning of the operative lung. The most obvious disadvantage of the DLT in the pediatric population is its size limitation. Because of its configuration and larger diameter, the DLT is more challenging for patients with difficult airways. When lung isolation is not needed, the bronchial cuff should be deflated to decrease the risk of mucosal injury. If postoperative intubation and ventilation are required, the DLT should be replaced with an SLT to avoid unnecessary trauma to the tracheal-bronchial tree [20].

Double-lumen tubes are safe and easy to use. There are very few reports of airway damage from DLTs in adults and none in children. Their high-volume, low-pressure cuffs should not damage the airway if they are not overinflated with air or distended with nitrous oxide while in place.

The most important problem associated with the use of a DLT is malpositioning [53, 54]. The tube can be mispositioned in several ways.

The DLT may be accidentally directed to the side opposite to the desired main stem bronchus. In this case, the lung opposite the side of the connector clamp will collapse. Inadequate separation, increased airway pressures, and instability of the DLT usually occur. Because of the morphology of the DLT curvatures, tracheal or bronchial lacerations may result. If a left-sided DLT is inserted into the right main stem bronchus, it obstructs ventilation to the right upper lobe. It is essential to recognize and correct such a malposition as soon as possible. The DLT may be passed too far down into the right or the left main stem bronchus. In this case, breath sounds are greatly diminished or not audible over the contralateral side. The tube should be withdrawn until the opening of the tracheal lumen is above the carina.

5.4.5 Strategies for Treating and Avoiding Hypoxemia During Single Lung Ventilation

Successfully performing SLV involves not only achieving lung isolation and collapse but also ensuring that oxygenation of the patient is well maintained. The following measures have been found useful in avoiding or treating hypoxemia [53]:

- Ensure correct placement of the SLV device in use (blocker or ETT). It is advisable to confirm the position of the device used after positioning the patient to rule out inadvertent displacement that may have occurred during patient positioning
- Ventilation with 100% oxygen is recommended because it not only provides a higher margin of safety but also causes vasodilatation of vessels in the dependent ventilated lung, thereby promoting redistribution of blood from the nondependent unventilated lung
- Keep the inspired concentration of the inhaled anesthetic agent to less than 1 minimum

alveolar concentration (MAC) to avoid excessive inhibition of HPV and decrease in cardiac output
- Use of 5–10 mL/kg body weight tidal volume. If the inflation pressure is high, the respiratory frequency may be increased at lower tidal volume to avoid excessive airway pressures
- Application of CPAP to the nondependent lung improves oxygenation by preventing the total collapse of the alveoli [54–56]
- A useful increase in oxygenation can be achieved with pressure as low as 1–2 cm H_2O CPAP applied to the inflated lung [57, 58]
- CPAP commenced after lung inflation is more effective than CPAP commenced from a fully deflated lung because the opening pressure of collapsed alveoli is higher than the CPAP pressure. CPAP greater than 10 cm H_2O should be avoided because it may lead to excessive inflation of the operative lung and interfere with the surgical procedure
- Application of 5–10 cm H_2O positive end-expiratory pressure (PEEP) to the dependent ventilated lung is helpful in some patients. This level of PEEP does not cause a significant increase in pulmonary vascular resistance that may result in diverting blood to the unventilated lung, leading to an increase in the shunt
- Adequate cardiac output must be maintained to ensure good tissue perfusion to prevent an excessive decrease in mixed venous oxygen content. Because these patients have a large shunt (20–30%), high mixed venous oxygen content will help in decreasing the effect of shunted blood in causing arterial desaturation.

5.4.6 Conclusion

To overcome the challenges of rendering one-lung ventilation technique in infants and children coming for video-assisted thoracoscopic surgery, one must be mindful of the respiratory insult caused by SLV under general anesthesia and positioning during the operation. Although it is prudent to use a device one is technically familiar with, the anesthetists must also be aware of whether if it is appropriate for the patients' age and weight (Table 5.3). Furthermore, if the device is equipped with safety features such as ventilating both lungs in the event of hypoxia, and if it can provide efficient lung isolation intraoperatively. The anesthesiologist caring for patients who require SLV and lung isolation faces many challenges. An understanding of the primary underlying lesion, as well as associated anomalies that may affect perioperative management, is paramount. Working knowledge of respiratory physiology and anatomy is required for the planning and execution of appropriate intraoperative care. Familiarity with a variety of techniques for SLV suited to the patient's needs allows maximal surgical exposure while minimizing trauma to the lungs and airways.

Table 5.3 Advantages and disadvantages of the different tubes

Single-lumen endotracheal tube	Double-lumen endobronchial tube	Balloon-tipped bronchial blockers
Advantages		
No special equipment	Faster positioning	Ideal for patients with complex airways
Preferred in emergencies	Complete lung isolation	Best device for infants and children
	No bronchoscope needed for positioning	No replacement for postoperative ventilation is required
	Lower risk of displacement	Selective lobar blockade
	It can be used in mono and bi ventilation	
Disadvantages		
Risk of hypoxemia	Only patient older than 8 years	The transition from mono to biventilation is complex
The bronchus is not perfectly sealed	Need to replace the tube at the end of the procedure	Requires high skills in positioning
	Risk of trachea-bronchial injuries	Easly dislocation, requires a lot of maintenance

5.5 Anesthesiologic Management of the Main Surgical Pathologies in Pediatric Population

5.5.1 Congenital Lung Lesions

1. **Congenital lobar emphysema (CLE).** CLE is a postnatal abnormal overdistension of an otherwise anatomically normal lobe of the lung that communicates with a bronchus [59]. Progressive hyperinflation of the lobe occurs either due to anomalies of bronchial cartilage or due to external bronchial compression with resultant air trapping on expiration [60]. Usually, CLE is monolateral, and the upper lobes are most affected while lower lobes are usually spared. CLE generally presents in full-term neonates during the first 6 months of life; the clinical features depend on the degree of overdistension and the consequences on surrounding tissues. Tachycardia, tachypnea, retractions, cyanosis, grunting, and coughing may be present. The chest may present asymmetric with decreased breath sounds over the affected lobe.
2. **Congenital pulmonary adenomatoid malformation (CPAM).** CPAM is a lung lesion that develops from adenomatous overgrowth of terminal bronchioles without simultaneous alveolar growth. It comprises about 25% of all congenital lung malformations, with an estimated incidence of 1/25000–1/30000. The lesion may be cystic, solid, or mixed, and generally, it communicates with the tracheobronchial tree, while arterial supply and venous drainage are provided by the pulmonary circulation. CPAM may become overdistended due to air trapping and cause compression and shifting of the mediastinal structures. Spontaneous pneumothorax, pneumonia, or lung abscess may also develop. About 80% of the affected infants present some degree of respiratory distress. Signs and symptoms include tachypnea, grunting, retractions, cyanosis, and failure to thrive. If lesions are small, infants may be asymptomatic, but generally, it has been detected on prenatal ultrasonography and/or MR imaging.
3. **Pulmonary sequestration.** In this case, the malformation involves an abnormal, malfunctioning part of lung tissue not communicating with a bronchial tree. The blood supply comes from systemic abnormal arteries. It may be intralobar (90%) or extralobar. Infants with intralobar sequestrations are otherwise generally healthy, while those affected by extralobar lesions present frequent associated congenital anomalies such as congenital diaphragmatic hernia (CDH) or chest wall deformities. Children with pulmonary sequestrations generally present recurrent pneumonia involving the same lobe or adjacent atelectatic pulmonary tissues after the first or the second year of life. Because of the systemic arterial supply, children may develop high-output cardiac failure from shunting through the sequestration.

5.5.1.1 Anesthesia Consideration and Management of Congenital Lung Malformations

- Small patients present an increased risk of respiratory adverse events because of their particular age-specific characteristics and because of the effects of anesthesia on pediatric lung function [61]. A complete preoperative evaluation is mandatory to evaluate the degree of preoperative pulmonary compromise, the pathophysiology of associated lesions, the consequences of surgery, and the ability to tolerate SLV. Preoperative evaluation requires a chest X-ray, TC scan, and an echocardiogram to rule out congenital heart diseases and to evaluate cardiac function. The preoperative bronchoscopic examination may be useful in patients with CLE to evaluate the presence and the degree of bronchial stenosis and its possible reversibility.
- Neonates with relevant cardiopulmonary compromise necessitate intubation and ventilation in the pediatric intensive care unit (PICU) before surgery.
- While CLE usually necessitates a complete thoracotomy lobectomy, CPAM and pulmonary sequestration may be excised with a thoracoscopic segmental resection that requires SLV(see above).

- Inhalation or intravenous (IV) induction may be performed; patient affected by CLE and CPAM should be intubated without muscle relaxation and spontaneous ventilation maintained until either the chest is opened (thoracotomy) or SLV is established (thoracoscopy) because air trapping may cause overdistension of the affected lobe, compression of the normal lung, mediastinal shift, and a reduction in cardiac output [62]. If necessary, positive pressure ventilation or hand ventilation may be used at low peak inspiratory pressure.
- Infants are predisposed to hypoxemia because of their elevated oxygen consumption (8–10 mL/kg/min vs 3–5 mL/kg/min in adults), their small functional residual capacity (FRC), and their more compliant chest wall which cannot completely support the dependent lung in a lateral position [63]. As a consequence of this, FRC gets closer to residual volume and alveolar collapse occurs more easily [15]; in addition, shifting of the mediastinum, compromised venous return, and decreased cardiac output may all cause impaired gas exchange, hypoxemia, and hypotension [64].
- FiO_2, peak inspiratory pressure (PIP), tidal volume (TV), and PEEP should be calibrated on SpO2 and $EtCO_2$ keeping in mind that a decreased pulmonary blood flow may be responsible for a decreased $EtCO_2$. An arterial line for continuous pressure monitoring and to check pH, partial pressure of oxygen (PO_2), partial pressure of carbon dioxide(PCO_2), glucose, and hematocrit are always required. A certain degree of hypercarbia may be tolerated in order to avoid ventilator parameters and to reduce the risk of volume and barotrauma. Nitrous oxide is contraindicated in the case of CLE because of its ability to expand empty body cavity [65]. Balanced, total intravenous, or blended (general/thoracic epidural) techniques may be used for maintaining anesthesia.
- Temperature monitoring is critical because children lose heat rapidly; every effort must be used to maintain optimal body temperature.
- Due to the proximity of great vessels, blood should be available in the operating room.
- At the end of most of the thoracic procedure, older children may be extubated; neonates and infants undergoing thoracic surgery are admitted to PICU for postoperative monitoring and those with high degree of cardiopulmonary compromise postoperative ventilation will be necessary.

Sedatives are used for pain control and to maintain a good adaptation to the ventilator in order to avoid developing air leaks at the bronchial sutures.

5.5.2 Congenital Diaphragmatic Hernia

Congenital diaphragmatic hernia (CDH) is the result of the failure of fusion of the components of the diaphragm in early embryogenesis; the herniation of abdominal contents into the chest may be paraesophageal, retrosternal, or, the most common, posterolateral (Bochdalek hernias, 90%); the majority of them occur on the left side. The lung parenchyma and the pulmonary circulation always present some degrees of hypoplasia, while the heart and the mediastinum are often displaced. Mortality correlates with the size of the defect, the degree of pulmonary hypoplasia, the gestational age, the birth weight, and the presence of additional abnormalities as part of a syndrome or chromosomal abnormality.

Almost all affected newborns present respiratory distress due to pulmonary parenchyma and pulmonary vascular hypoplasia; pneumothorax and pulmonary hypertension may worsen child conditions. Patency of ductus arteriosus and communication at the atrial level will determine the right to left shunting due to increased pulmonary resistance. Rapidly after birth hypoxemia, hypercarbia and acidosis will develop.

Immediate intubation and ventilation are necessary; 100% FiO_2, high-frequency oscillatory ventilation (HFOV), and nitric oxide may be necessary to maintain adequate gas exchange; in some cases, extracorporeal membrane oxygenation (ECMO) is required.

5.5.2.1 Anesthesia Consideration and Management of Neonates with CDH

- Surgery is often performed in PICU in order to avoid destabilization of patients during transportation to the operating room and to maintain advanced ventilatory support.
- Pre- and postoperatory brain ultrasounds must be performed to check the presence of intracranial hemorrhage and its extension.
- Almost all neonates affected are submitted to the anesthesiologist fully prepared by a neonatologist who managed postnatal stabilization: ETT, arterial line, central venous line, nasogastric (NG) tube, and urinary catheter are mandatory.
- If neonates are not yet intubated induction of anesthesia should be planned carefully: anesthesiologist may decide between intubation under mild sedation(the best choice for neonates or small infants) or rapid sequence intubation with propofol, opioid, and rocuronium (the latter if he doesn't recognize the sign of difficult intubation).
- Aspiration of gastric contents with an NG tube is necessary before induction.
- Monitoring will include preductal pulse oximeter and pre or postductal arterial line for continuous pressure monitoring and blood samples in order to check gas exchange being aware that arterial oxygen saturation may be affected by the right to left shunting; near-infrared spectroscopy (NIRS) monitoring is strongly suggested.
- Balanced or total intravenous anesthesia may be chosen.
- Ventilation and oxygenation may be challenging: if possible, maintain PIP under 30 cm H_2O and be aware of contralateral pneumothorax; 100% FiO_2 is frequently indispensable and nitric oxide may be necessary to maintain oxygenation (preductal SpO_2 goal = 90–95%).
- Intraoperative infusion of inotropic drugs (adrenaline or dopamine) and volume infusion are frequently needed to support cardiac function and maintain adequate systemic arterial pressure values.
- Be aware of intraoperative hypoglycemia, acidosis, and hypothermia.
- Postoperative ventilation and sedation are always necessary.

5.5.3 Tracheoesophageal Fistula and Esophageal Atresia

The incidence of tracheoesophageal fistula (TEF) is between 1:3000–1:4000 live births. In 80–85% of neonates, it is associated with esophageal atresia (EA). About 30% of babies with TEF are born prematurely. A common association is the VACTERL complex, including vertebral, anorectal, cardiac, tracheoesophageal, renal, and limb defects. Birth weight <2.000 g and cardiac defects represent the greatest risk factors for increased mortality [66].

The classification of TEF was developed by Gross who described types A through F.

Type C, proximal atresia with distal fistula slightly above the carina, is the most common (85–90%).

EA/TEF may be suspected on prenatal ultrasonography in the case of maternal polyhydramnios and, in the case of proximal fistula, by the absence of stomach bubble.

Postnatal presentation is characterized by excessive salivation, vomiting after feeding, and coughing; respiratory distress and cyanosis are the results of aspiration as the blind esophageal pouch fills and by reflux of gastric contents up the distal esophagus into the lungs through the fistula.

EA is diagnosed by the inability to pass a catheter into the stomach; a chest X-ray will show the catheter in the blind esophageal pouch, while the presence of air into the stomach will reveal the presence of a distal TEF. A preoperative echocardiogram and a renal ultrasound are necessary for every child affected by TEF and/or EA to identify cardiac or renal anomalies, which, when present, may affect anesthetic management [67].

Isolated TEF is usually treated during the first or second month of life, through a right cervical incision, and less frequently through a right thoracotomy or thoracoscopy. EA without fistula can be managed with a gastrostomy and surgically

repaired at the age of 2–3 months in a unique surgical stage. EA/TEF is surgically repaired during the first week of life, traditionally through a right thoracotomy. The thoracoscopic approach has been recently introduced in tertiary-level pediatric hospitals and is becoming increasingly popular for a positive outcome.

5.5.3.1 Preoperative Airway Management of TEF/AE

- At the time of PICU admission, a fiberoptic bronchoscopy is always performed to visualize the upper respiratory tract anatomy and the TEF position.
- Spontaneous ventilation is the best option to avoid air leak into the stomach; when lung compliance is optimal, spontaneous ventilation should be maintained with continuous suctioning of the proximal esophageal pouch in order to avoid gastric distension and acute pneumoperitoneum, the two-life threatening complication that may occur in ventilated children with large TEF.
- In case of poor lung compliance, tracheal intubation is needed; the tip of the tube is positioned below the TEF under direct vision and the ventilator is set at the minimal required positive pressure. In case of large TEF or TEF positioned at the level or below the carina most of the air flow may direct to the stomach; in this case, a balloon-tipped catheter may be placed in the fistula under direct bronchoscopic vision. In case of massive distension and difficult ventilation, abdominal decompression could be acutely needed.

5.5.3.2 Anesthesia Consideration and Management of Infants with TEF/AE

- Induction of anesthesia can be performed with inhalational sevoflurane in a mixture of oxygen and air. Spontaneous breathing can be safely maintained and intubation can be performed under deep sedation. As discussed earlier, the tip of the tracheal tube is positioned below the TEF under direct vision. Small doses of opioids like morphine or fentanyl can be administrated to reduce the risk of coughing. The other option is apneic intubation using preintubation neuromuscular blockades. In this case, a bagging with low pressure is mandatory to minimize air leak through the TEF. Otherwise, this will not the case of large TEF or patients with poor lung compliance or both.
- Intraoperative anesthetic drugs are not widely standardized. Sevoflurane is the general anesthetic most frequently used in combined with fentanyl or remifentanil. The last one, despite the risk of hypotension, permits a flexible change of the anesthetic level in a short period of time. Paralysis during surgery is mandatory; both rocuronium and cisatracurium may be used.
- Careful monitoring is required in these patients. An arterial line for continuous pressure monitoring systematic and intraoperative blood gases central lines inserted in all neonates undergoing AE/TEF repair. A central venous line is recommended to administrate fluids and catecholamines.
- Mechanical ventilation is challenging even for the experienced pediatric anesthetist. Accidental intubation of the TEF, air leak from the TEF, coexisting pulmonary pathologies, prematurity, and thoracoscopy can be listed as possible risk factors.
- Once obtained, tracheal intubation with the tip of the tube below the TEF, paralysis, and mechanical ventilation can be safely obtained.
- The commonly performed surgical approach for thoracoscopic repair is from the right side. In the case of right-sided aortic arch, the surgical access is from the left side.
- Single lung ventilation is required to optimize the surgical view and manipulation. Specific devices for single-lung ventilation as bronchial blockers or double-lumen tubes are not available for neonates [68], but thoracoscopic view can be achieved with double lung ventilation. Pressure insufflate for thoracoscopy is usually 5 mmHg, and this is enough for lung compression. Surgeons can push away the lung from the posterior mediastinum to improve the view and space for surgical repair.

- Pressure-controlled ventilation (PCV) is usually preferred because adequate lung volume can be achieved with lower peak inspiratory pressure (PIP) compared to volume-controlled ventilation (VCV). The lower PIP is a consequence of a limited and constant inspiratory pressure and a decelerating flow. The combination of these factors over time improves gas exchange [69].
- PIP, positive end-expiratory pressure (PEEP), respiratory rate, and fraction of inspiratory oxygen are regulated step-by-step to maintain acceptable respiratory and metabolic parameters.
- All patients undergoing TEF/AE repair are admitted to PICU for postoperative ventilation and monitoring.

Sedatives are used for pain control and to maintain a good adaptation to the ventilator to avoid the dehiscence of the suture.

5.5.4 Mediastinal Masses

Primary thoracic neoplasms in children are rare [70]. Mediastinal masses are more common than intrapulmonary masses in children [71] and their anesthetic management may be challenging due to the severe complications that can originate during induction and maintenance of general anesthesia [72]. In younger patients, these tumors may be asymptomatic or present with symptoms like cough, stridor, dyspnea, and cyanosis; older children and adolescents may present cough, dyspnea, and in the most severe cases orthopnea. The presence of orthopnea may be predictive of tracheal compression, and it should be assessed in every patient. The tumor may compress the heart and the great vessels, and the patients may present cardiovascular signs as hypotension, arrhythmias, and superior vena cava (SVC) syndrome.

Computed tomography (CT) scans are necessary to evaluate the degree of tracheal and cardiovascular compression, and in the most symptomatic patients, it must be performed without or only with a mild sedation in order to avoid exacerbation of the symptoms. Careful titration of sedative drugs such as midazolam, ketamine, or propofol or alternatively small concentration of sevoflurane may be sufficient for sedation of uncooperative children.

Patients with cardiovascular symptoms, sign of cardiac or great vessels compression, or with SVC syndrome must be submitted to echocardiography.

5.5.4.1 Anesthesia Consideration and Management of Children With Mediastinal Mass

- During general anesthesia, children with a mediastinal mass are at risk of total airway obstruction and cardiovascular collapse due to exacerbation of extrinsic airway and/or cardiovascular compression.
- Prediction of anesthesia-related risk is difficult. Anghelescu et al. found that orthopnea, SVC syndrome, and mainstem bronchus compression were the main preoperative features significantly associated with anesthetic complications [73]; regarding radiological findings, other authors [74] found that maximum risk is present when the tracheal cross-sectional area is less than 50% of normal on CT scan. In these cases, careful consideration should be given to performing a biopsy under local anesthesia or initiating chemotherapy or limited radiation therapy prior to subjecting the child to general anesthesia [75].
- Intraoperative management includes the use of short-acting anesthetics, avoidance of muscle relaxants, and, if possible, maintenance of spontaneous breathing. If a patient is susceptible to airway obstruction, mask induction with sevoflurane in 100% oxygen is preferred to intravenous induction in order to maintain spontaneous ventilation and airway patency. Alternatively, IV titration of propofol, ketamine, and/or dexmedetomidine which maintains spontaneous ventilation may be used. If the patient presents severe orthopnea, induction of anesthesia should be in sitting position, intravenous access should be placed in the lower extremities, and a rigid bronchoscope and experienced bronchoscopist must be available [76]. As soon as possible, an arterial

line should be placed for monitoring arterial pressure. If an ETT placement is necessary, an armored tube should be used and positioned with its extremity distal to the compressed portion of the trachea. This maneuver may be impossible, and the anesthesiologist must be forced to put the tip of the tube proximal to the obstructed airway then checking if good ventilation may be established.

- Airway obstruction may significantly worsen with positive pressure ventilation, and the anesthesiologist must be ready to put the patient in a lateral position in order to reduce the compression on the airway. The possibility to reestablish good ventilation and oxygenation with a ventilating rigid bronchoscope or with jet ventilation through a rigid bronchoscope have both been described as viable solutions but they are probably very difficult to achieve in most cases.
- In adolescents and children weighing more than 30 kg with severe clinical symptoms and large mediastinal anterior tumor may be indicated the isolation of femoral vessels in mild anesthesia supported by local anesthesia to provide for the availability of cardiopulmonary bypass before proceeding to tracheal intubation and positive pressure ventilation.
- Once the induction has passed and good ventilation and oxygenation have been established, maintenance of anesthesia must be performed by both total intravenous or balanced anesthesia; careful monitoring of cardiovascular and respiratory parameters is mandatory during surgery.
- If surgery is completed without complications, patients may be extubated in the operating room and carefully monitored in the immediate postoperative period.

5.5.5 Pectus Excavatum Or Carinatum

Pectus excavatum and carinatum are the most common morphological chest wall abnormalities [77]. In pectus excavatum, several ribs and the sternum grow abnormally producing a concave deformity of the anterior chest wall. It can be diagnosed at a very young age or, more commonly, it may become noticeable in the early teenage years. Pectus excavatum is the most common type of congenital chest wall deformity (90%) with an estimated incidence of 1 in 300–400 birth with male predominance (3:1). Pectus carinatum is defined by the anterior protrusion of the sternum and adjacent cartilages [78]. Pectus excavatum and carinatum are often associated with scoliosis. Many patients are brought to the attention of the surgeon during adolescence when the appearance of the chest becomes very disturbing to young teenagers. Patients with pectus excavatum may present with a wide range of symptoms; most of them do not have cardiorespiratory symptoms even in the presence of mildly abnormal function tests [79], while others complain of dyspnea during exercise, palpitations, and chest pain. Mitral valve prolapse may be present in about 30–60% of patients.

5.5.5.1 Anesthesia Consideration and Management of Patients with Pectus Excavatum/ Carinatum

- Surgical repair is always performed during adolescence and the minimally invasive Nuss technique [80] and its modifications [81] is the method of choice for last 20 years.
- Imaging studies include posterior–anterior and lateral chest X-ray and thoracic CT scan.
- Echocardiography is necessary for patients suspected of Marfan syndrome to evaluate for possible aortic root dilation.
- Pulmonary function tests are needed especially for patients symptomatic with exercise.
- A combination of general endotracheal anesthesia, thoracic epidural, or cryoanalgesia is the methods of choice.
- Standard monitoring plus an arterial line is generally used.
- In adolescents, a thoracic epidural catheter may be placed before anesthesia under mild anxiolysis; it should remain in place for 48–72 h postoperatively. A segmental epidural blockade should be the goal with approxi-

mately 2 mL of local anesthetic per segment to be blocked administered [82].

- A total intravenous technique with target-controlled infusion (TCI) of propofol and remifentanil is generally used.
- Muscle relaxation is necessary to facilitate intubation and result useful to optimize surgical conditions.
- At the end of the surgical procedure, the anesthesiologist must inflate the lung by manual application of large tidal breaths in the Trendelenburg position in order to avoid the placement of a chest tube.
- Emergence agitation and pain often require the administration of morphine and sedatives.
- Patient-controlled analgesia (PCA) and FANS with or without thoracic epidural are always used to control postoperative pain.

5.6 Management of Postoperative Pain

Appropriate treatment of postoperative pain contributes to a shorter time of hospitalization, lower hospital costs, and increased level of patient satisfaction [83]. Ideally, every hospital should have a system for providing patients safe and effective analgesia when they are experiencing acute pain after surgery [84]. After thoracic surgery pain management is important to keep the child comfortable to avoid pulmonary dysfunctions such as atelectasis and postoperative infection and to facilitate earlier mobilization. Post-thoracotomy pain is considered as one of the most intense postoperative pain, whereas it appears less acute after VATS; for these reasons, as a general guideline, complex analgesic techniques are used in the events of open thoracotomy while after VATS pain may be controlled with systemic non-opioid analgesics [2]. Post-thoracotomy pain is exacerbated by breathing, coughing, movements, and respiratory physiotherapy, so in the first 48–72 h, the patients need to be managed with an association of patient-controlled analgesia (PCA) or parents/nurses controlled analgesia (PNCA) with morphine, locoregional techniques, and systemic non-opioid analgesic.

Options for locoregional analgesia include:

- intercostals nerve blocks performed prior to skin incision or at the end of surgery just before surgical closure under direct visualization
- paravertebral block with local anesthetic injection in the paravertebral space, performed through single-shot or continuous techniques
- continuous thoracic epidural analgesia through a catheter placed in the epidural space with the tip positioned at the dermatome level corresponding to the surgical incision.

Although newer techniques have been developed, pediatric epidural analgesia is an accepted method of advanced analgesia in children [85]. The technique of catheter placement is the same used in adults except for the timing of placement as anesthesia is often required for a safe maneuver.

Many different local anesthetic solutions and adjuvants have been used in the pediatric population. The most popular local anesthetics used are levobupivacaine and ropivacaine [86]; clonidine and opioids are commonly co-administered, as they reduce the dosage requirement for local anesthetics and improve the block quality. While the safety profile of epidural clonidine justifies its systematic use, opioids may cause respiratory depression; thus in the case of their epidural use for postoperative pain control, patients should be strictly monitored and an acute pain service staff should be available to provide timely response to any complications. In the author's experience, the association of ropivacaine or levobupivacaine with clonidine may be the right choice for safe and successful management of post-thoracotomy pain.

Table 5.4 shows the suggested doses to be administrated in the pediatric population.

In conclusion, after thoracic surgery children need proper management of postoperative pain that should be considered as an essential part of anesthesia; for this reason, anesthesiologists

Table 5.4 Local anesthetics and clonidine for continuous epidural analgesia

		Bolus		Continuous infusion		
		Local anesthetic	Adjuvant	Anesthetic solution	Rate	Others bolus
Age <12 months	< 5 kg	Ropivacaine 0.2% 0.6–0.8 mL/kg	Clonidine 1–2 mcg/kg	Ropivacaine 0,1% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h	0.6 mL/kg of solution
	> 5kg < 10kg	Levo-Bupivacaine 0.5–0.2% 0.6–0.8 mL/kg	Clonidine 1–2 mcg/kg	Ropivacaine 0,1% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h	0.61 mL/kg of solution
Age >12 months	10–25 kg	Levo-Bupivacaine 0.2% 0.6–0.8 mL/kg	Clonidine 2 mcg/kg	Ropivacaine 0.125% Clonidine 1mcg/mL	0.2–0.4 mL/kg/h Max 10 mL/h	0.61 mL/kg of solution Max 15 mL
	25–40 kg	Levo-Bupivacaine 0.25% 0.6–0.8 mL/kg	Clonidine 2 mcg/kg	Ropivacaine 0.125% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h Max 15 mL/h	10–15 mL of solution
	>40 kg	Levo-Bupivacaine 0.375% 10–20 mL max 20 mL	Clonidine 2 mcg/kg Max 100 mcg	Ropivacaine 0.125% Clonidine 1 mcg/mL	0.2–0.4 mL/kg/h Max 15 mL/h	10–20 mL of solution

who care for children submitted to this kind of surgery must be familiar with the use of techniques as PCA/PNCA and epidural thoracic anesthesia/analgesia and should be supported by an acute pain service staff for daily surveillance of efficacy and safety of pain therapy.

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6 Extracorporeal Membrane Oxygenation

Andrea Moscatelli and Simona Tani

6.1 Introduction

ECMO (Extracorporeal Membrane Oxygenation) is a device derived from the cardiopulmonary bypass (CPB) machine used during open-heart surgery. It has been introduced in clinical practice at the beginning of the 1970s [1]. ECMO can substitute the function of the lungs (veno-venous, VV-ECMO), the heart, or both (veno-arterial, VA-ECMO) when respiratory, cardiac, or cardiopulmonary failure are not responding to maximized conventional medical treatment. The first successfully treated adult patient has been reported in 1972, while the first surviving pediatric cases are from 1974 [2].

In extreme synthesis, ECMO is able to oxygenate blood, remove the CO_2, and convey oxygenated and de-carbossilated blood to tissues.

A. Moscatelli (✉)
Neonatal and Pediatric ICU, Critical Care ECMO and Transport Team, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: andreamoscatelli@gaslini.org

S. Tani
Division of Cardiovascular Surgery, Perfusion Team, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: simonatani@gaslini.org

6.2 Hardware

The pump is the heart of the ECMO system. It drains blood from the patient's venous side of the systemic circulation, pushing it through the oxygenator. The oxygenator, as an artificial lung, removes CO_2 and oxygenates blood. Blood is then pumped back to the patient on the venous or arterial side of the systemic circulation, according to the specific ECMO modality. The oxygenator is coupled with a heat exchanger warming blood before it is reentered into the patient's heart or vessels. The portion of the circuit upstream to the pump is called venous or drainage side (limb), while the downstream one is defined as arterial or infusion/return side (limb) (Fig. 6.1).

6.2.1 ECMO Pumps

Pumps function as the "heart" of the ECMO circuit.

Roller pumps: They use the same technology utilized for CPB machines and are referred to as constant flow pumps. A rotor compresses a tube of a known diameter and length placed within a rigid raceway. Knowing the length of the tube, its diameter, and the number of compressions per minute, it is possible to mathematically calculate flow (Fig. 6.2). Flow is dependent on venous drainage, which is mostly passive, even if negative pressures can be generated on the "venous"

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_6

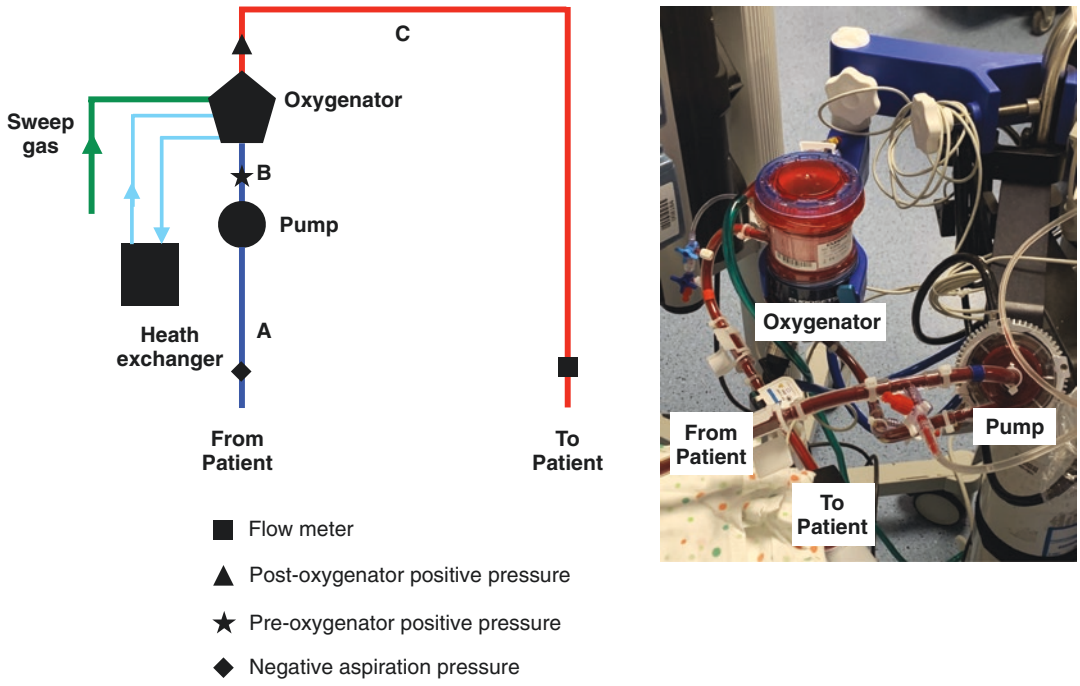

Fig. 6.1 Scheme of an ECMO circuit. Venous limb or drainage (pre-pump), A; arterial limb (post-pump), B + C. Deoxygenated blood, A + B; oxygenated blood, C

side of the circuit. In this case, the venous return does not match the forward flow and a switch, connected to a pressure sensor, stops the pump. A bladder (reservoir), placed on the venous limb, ensures a minimum reserve of venous return, making blood flow more constant and less dependent on passive drainage. On the contrary, blood flow is independent of resistances downstream to the pump ("arterial" limb of the circuit, vascular resistances of the patient). It is possible to clamp the arterial side of the circuit only if the pump is stopped. If not, the pump will continue to increase the pressure inside the circuit, potentially until the rupture limit is reached (Fig. 6.2).

Centrifugal pumps: With such pumps, flow is dependent on both the venous return and the resistances downstream to the pump. The rotation of an impeller generates a vortex of blood with a central negative pressure suctioning other blood from the venous side of the circuit. The blood is peripherally accelerated and pushed by centrifugal forces into the arterial limb (Fig. 6.3). Flow is not constant but basically dependent on the resistances downstream to the pump (circuit arterial limb and

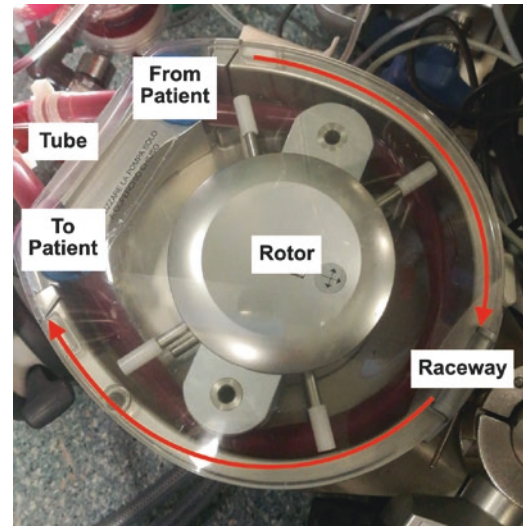

Fig. 6.2 Roller pump, the tube is compressed by a rotor within the raceway

patient's vascular resistances). To keep the generated flow constant, it is necessary to continuously monitor it, adjusting the rotation speed of the impeller (revolutions per minute, RPM); thus obtaining the target flow. If resistances increase,

higher RPMs will be needed to maintain a constant flow. Thus, positive pressures are dependent on the downstream resistances ("arterial" limb of the circuit, vascular resistances of the patient), and on the revolutions per minute. Proportional negative pressures are generated on the venous side. If the circuit is clamped downstream to the pump (Fig. 6.1b and c), the flow stops, while if the clamp is placed on the venous side (Fig. 6.1a), the impeller does not stop to rotate, creating high negative venous pressures with the risk of cavitation (bubbles generation). Thus, the clamping sequence is arterial-venous, with a reverse order at unclamping (venous-arterial).

Centrifugal pumps are currently widely used because of their performance and easy operation. We will refer to their use in the rest of this chapter.

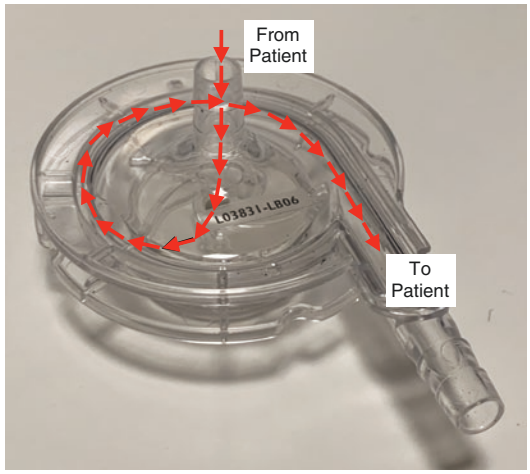

Fig. 6.3 Centrifugal pump

6.3 Oxygenator

The oxygenator should be considered as the "lung" of the system at which level the gas exchange occurs (Fig. 6.4). Gas exchange is extremely efficient since, with the newly designed oxygenators, a wide exchange surface is warranted. The blood and the gas phases are separated by a microporous membrane allowing only the movement of gas through it (Fig. 6.4c). This membrane is made of sheets of hollow fibers of polymethylpentene, thus the term "membrane lung". Blood flows between fibers, while gas is flowing inside of them (Fig. 6.4b). The oxygenator is structured in adjacent but sealed compartments (Fig. 6.4a). One compartment, in which the blood and gas flow occurs, contains the membrane sheets. In the other one a flow of heated water, coming from a servo-regulated heat exchanger, warms the blood to body temperature. Obviously,

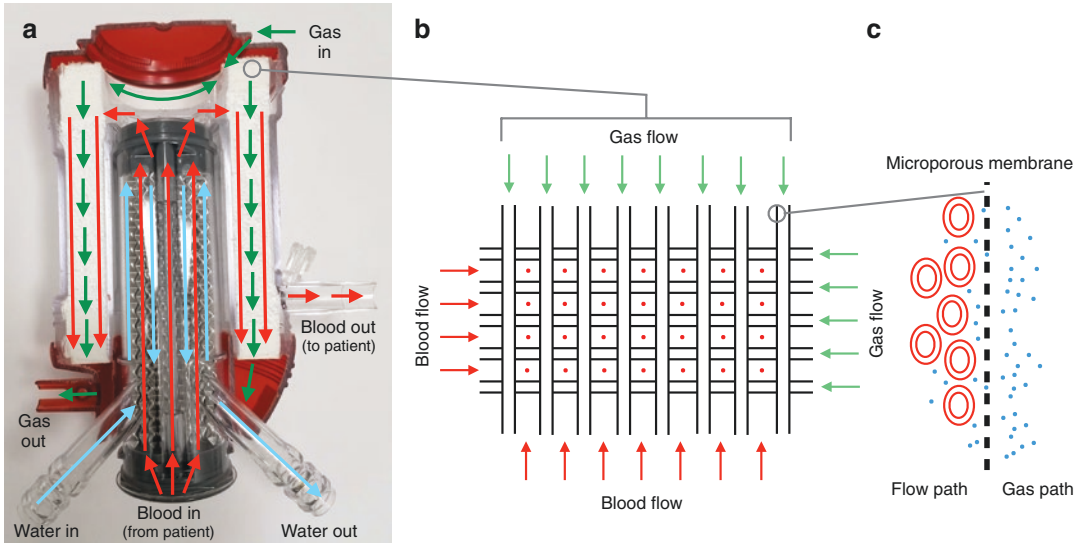

Fig. 6.4 The oxygenator. (**a**) Section of the oxygenator; (**b**) polymethylpentene membrane; (**c**) gas exchange interface

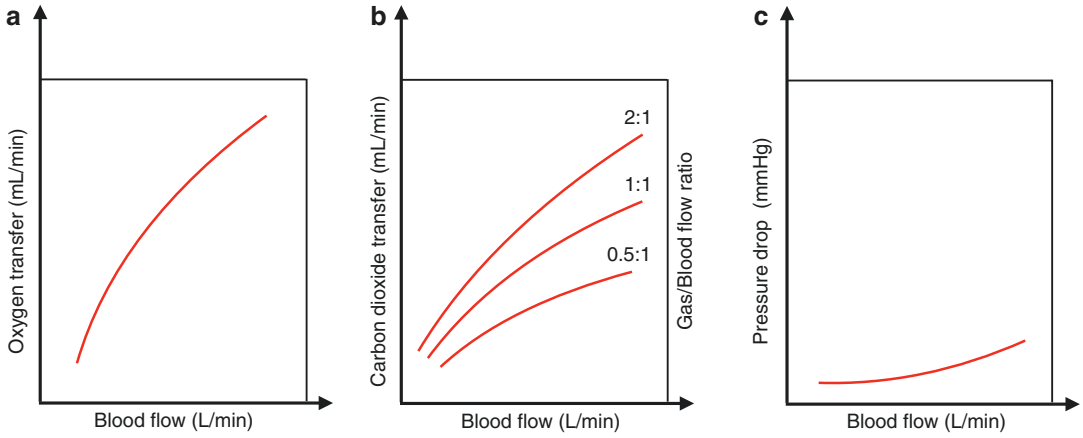

Fig. 6.5 Oxygenator performance charts. Oxygen delivery related to blood flow (**a**), carbon dioxide removal related to blood flow and different sweep gas/blood flow ratios (0.5:1, 1:1 and 2:1) (**b**), pressure drop across the oxygenator according to blood flow (**c**)

blood and gas have separated paths inside this latter compartment.

Oxygenation is primarily dependent both on the blood flow rate through the oxygenator and secondly on the sweep gas and its FiO_2. On the contrary, CO_2 removal is mostly dependent on the "sweep gas" flow. Usually, blood and sweep gas flow are set in a 1:1 ratio, but sometimes a higher rate is needed and should be regulated according to the target arterial CO_2. The maximum blood flow through the oxygenator, which determines the maximum oxygen delivery, depends on its constructive characteristics and cannot be exceeded. The pressure difference (pressure drop) between the blood inlet and outlet of the oxygenator is related to the structural characteristics of the membrane lung and to the blood flow. It is normal to have a pressure drop between 50 and 150 mmHg. An increase in the pressure drop might indicate aging of the oxygenator (clotting between fibers), with less effective gas exchange. The sweep gas is a mixture of air and oxygen. The FiO_2 is set with a blender according to patient's oxygen requirements and to the ECMO configuration (VV-ECMO or VA-ECMO), while the gas flow is adjusted with a precision flowmeter. On VV-ECMO, the FiO_2 is generally set at 0.9–1 (given the admixture of oxygenated-deoxygenated blood in the right atrium), while on VA-ECMO the FiO_2 is regulated according to the target PaO_2 and to the needed oxygen delivery. The performance of an oxygenator can be predicted with specific charts (Fig. 6.5) [3].

6.4 ECMO Configuration

6.4.1 Veno-Venous ECMO

VV-ECMO provides support only to the respiratory function. It might reduce the hemodynamic impact of mechanical ventilation allowing the application of gentler ventilatory settings. Blood is aspirated from the right atrium (RA) through a drainage cannula that is generally inserted from the internal jugular (IJV) or femoral vein (FV). It is re-entered into the venous circulation, close to the RA, with an infusion cannula inserted either from the IJV or FV. Another option is to utilize double-lumen jugular cannulas. Such catheters have one lumen dedicated to aspiration, while the other one serves for infusion with the infusion port directly facing the tricuspid valve (to limit recirculation, see further in the paragraph for explanation).

The most common VV-ECMO configurations are (Fig. 6.6):

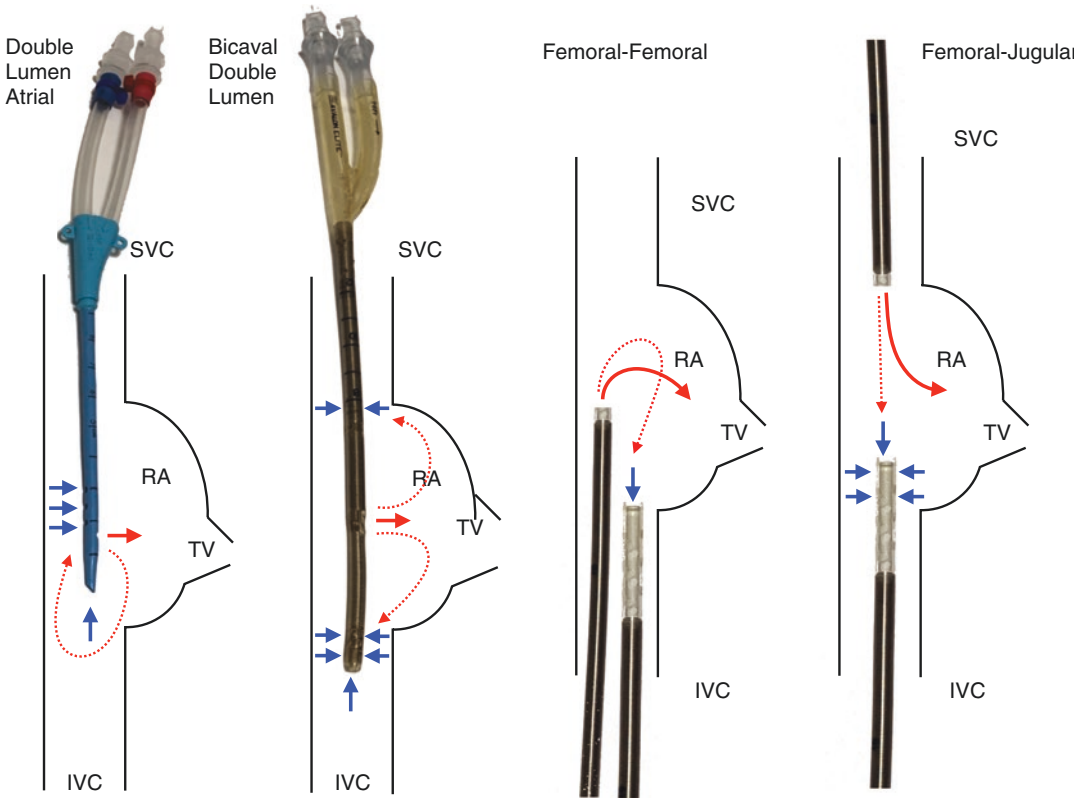

Fig. 6.6 VV-ECMO configurations (infusion ports, red solid arrows; aspiration ports, blue solid arrows; possible pathways of recirculation, red dotted arrows)

- Femoral–Femoral;
- Femoral–Jugular;
- Double-lumen atrial;
- Bicaval double lumen.

Oxygenated and deoxygenated blood mixes at the level of the right atrium in a 3:1 ratio, resulting in a saturation of the blood exiting the RA of 80–85%. VV-ECMO has several advantages compared to VA-ECMO:

- No requirement of arterial access (less risk of embolization and distal limb ischemia);
- The lungs and the coronary arteries are perfused with oxygenated blood (potent pulmonary vasodilator).
- A common problem with all the above-mentioned configurations is recirculation. A certain amount of oxygenated blood can be re-aspirated from the drainage cannula, thus limiting the oxygen delivery to the patient (desaturation), with an increase in the saturation of blood in the venous limb of the circuit. This phenomenon is mostly related to the reciprocal position of the infusing and aspirating cannulas (cannulas too close in the RA or directed one towards the other). Recirculation might happen even with double lumen cannulas, albeit they are designed to overcome this problem, especially the bicaval ones (Fig. 6.6, aspiration ports located in the SVC and IVC, distant from the infusion port, facing the tricuspid valve).

6.4.2 Veno-Arterial ECMO

VA-ECMO is able to provide respiratory support, cardiac support, or both. Blood is aspirated from the venous side and returned to the arterial side of

the circulatory system. There are two main modalities of VA-ECMO cannulation: central and peripheral.

Central cannulation: Cannulas are positioned, usually by an open chest, directly in the RA and in the aorta. This modality is generally reserved for patients needing cardiovascular support following open-heart surgery (Fig. 6.7). If the left ventricle (LV) is severely dysfunctional, it dilates with increased left ventricular and atrial pressures, leading to pulmonary edema. Decompression of the left atrium (LA) can be provided with an atrial septostomy or with an additional LA aspiration cannula. If the mitral valve (MV) is incompetent, this also ensures venting of the LV, reducing its wall stress, promoting adequate coronary perfusion, and preventing intraventricular thrombosis. Alternatively, the MV should be rendered temporarily insufficient by advancing an aspiration cannula from the left superior pulmonary vein into the LV. Another option is to directly vent the LV with an aspiration cannula placed through its apex. Venting of the LV can be obtained also percutaneously with a trans-aortic pigtail catheter, inserted from the femoral or axillary artery.

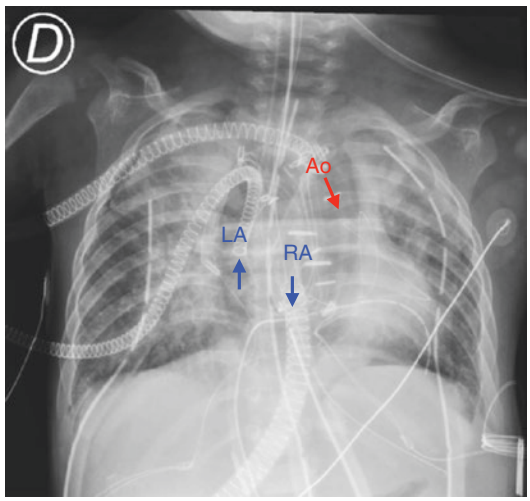

Fig. 6.7 Drainage cannulas in the right atrium (RA) and left atrium (LA), blue arrows; infusion cannula in the ascending aorta (Ao), solid red arrow

Peripheral cannulation: Blood is aspirated from a cannula with its tip positioned close to the right atrium (from the IJV or FV) and reinfused by the arterial cannula in the abdominal aorta (via the femoral artery) or in the ascending aorta (via the carotid artery) (Figs. 6.8 and 6.9).

Neck cannulation (IJV-carotid artery) is reserved for children weighing less than 15 kg, due to the small dimensions of the femoral vessels (Fig. 6.9), in bigger patients, the femoral approach is preferable, since it consents to preserve the carotid artery from ligation.

The same considerations made for LA and LV venting in case of central cannulation hold true for peripheral cannulation.

Atrial septostomy is generally preferred in small children, while the other strategies are taken into consideration in older ones (percutaneous trans-aortic or trans-thoracic surgical and apex venting).

At target flow, saturation of blood in the ascending aorta can be lower than 100% if the function of the lungs is compromised. In this case, some residual flow exists across the pulmonary circulation into the LA. The poorly oxygenated blood ejected from the aortic valve mixes with the oxygenated flow coming from the ECMO circuit, in a ratio up to 1:8. This admixture corresponds to an arterial oxygen saturation of about 94%.

During VA-ECMO for cardiovascular support, most of the venous return to the right atrium is diverted into the aorta with an almost complete bypass of the heart and the pulmonary circulation. The ejection fraction of the left ventricle (LV) is negligible, and the arterial flow is continuous (ECMO flow) with a flat invasive blood pressure arterial trace (Fig. 6.10). Instead, if the main reason for VA support is respiratory failure or if the heart is recovering, the differential pressure (systolic minus diastolic) is reduced, but a pulsatile trace might be present (Fig. 6.11).

6.4.3 Determinants of Flow

According to Poiseuille's law, the resistance to flow in a tube is directly proportional to the

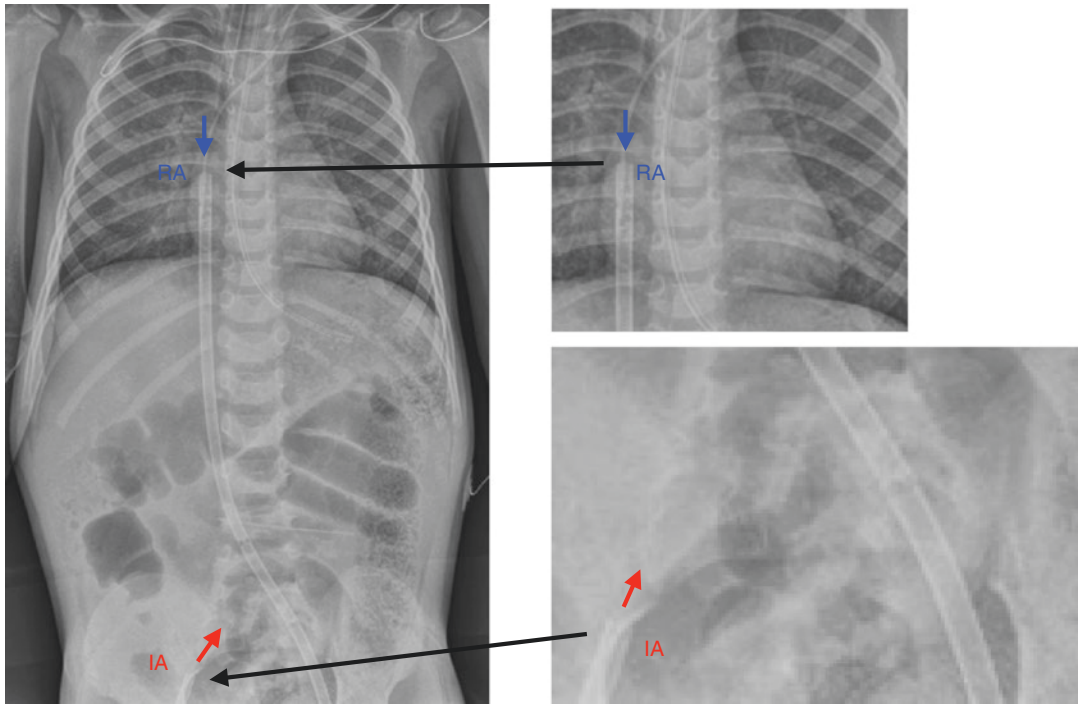

Fig. 6.8 Peripheral VA-ECMO, through femoral vein and femoral artery. Drainage cannulas in right atrium (RA), blue arrow, infusion cannula with the tip in the iliac artery (IA), red arrow

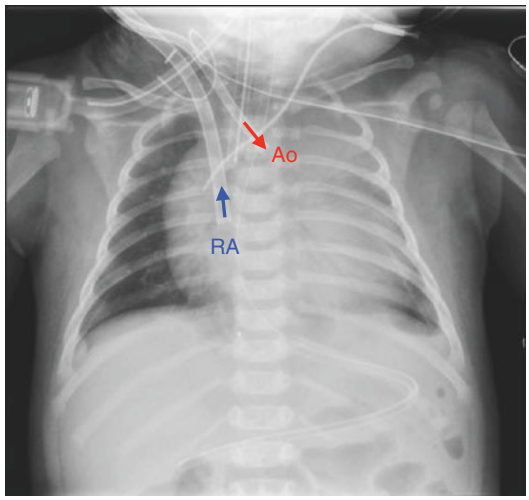

Fig. 6.9 VA-ECMO, through internal jugular vein and carotid artery. Drainage cannulas in right atrium (RA), blue arrow, from the jugular vein; infusion cannula with the tip in the ascending aorta (Ao), from the carotid artery, red arrow

length and inversely proportional to the fourth power of the radius (R α L/R4). Flow is generated on the venous side by the difference between the central venous pressure at the atrial level and the negative pressure at the inlet of the pump, on the arterial side by the difference in positive pressure between the outlet of the pump and the central venous (VV-ECMO) or arterial (VA-ECMO) pressure of the patient. Cannulas (venous and arterial) are the components of the circuit which more contribute to resistance to flow. The larger the cannula, the lower the resistance. It is acceptable to have negative pressures not lower than −100 mmHg on the aspiration limb (best if within the −70, −60 range). Excessive negative pressures, with flow limitation, can be due not only to cannula dimensions but even to reduce venous return. On the arterial side, a high resistance would lead to a reduction in flow (centrifugal pumps) or to excessive positive pressure if RPM are raised to maintain a constant flow. Both excessive negative and positive pressures increase the risk of hemolysis. Positive pressures should not exceed 400 mm Hg (best if within the 250, 300 range).

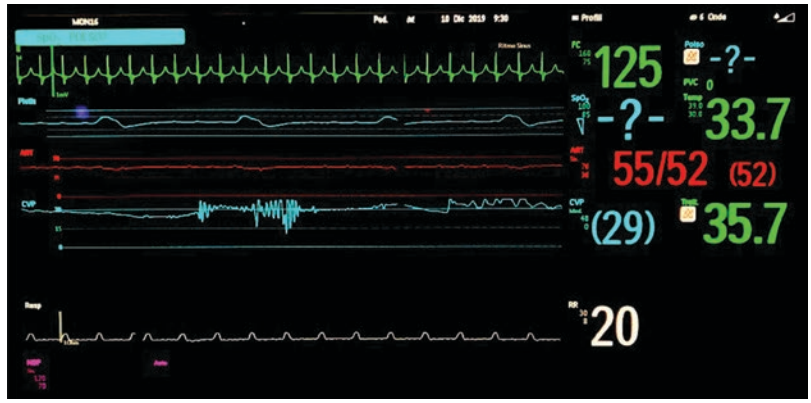

Fig. 6.10 VA-ECMO, severe cardiac dysfunction in full support, flat arterial trace

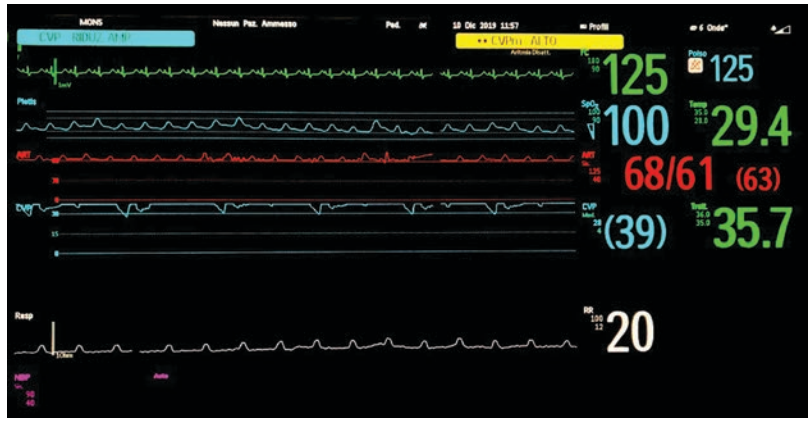

Fig. 6.11 VA-ECMO for respiratory support or initial LV recovery, pulsatile arterial trace with reduced differential pressure

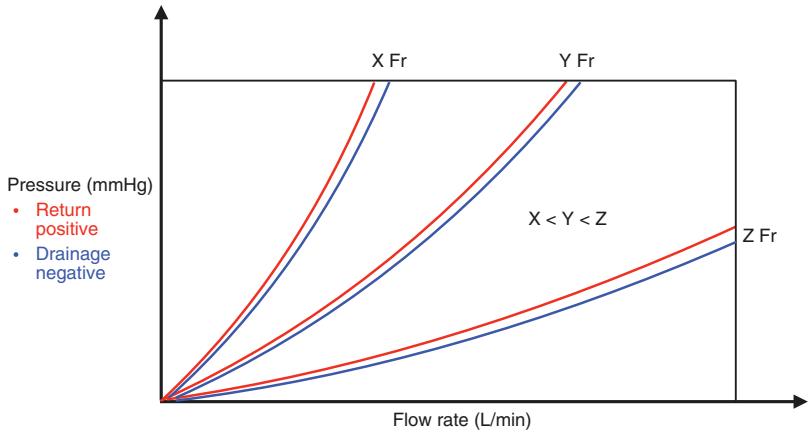

Fig. 6.12 Pressure is plotted against flow for different cannula sizes. In red the positive pressure difference (pressure drop) across the infusion (return) cannula, in blu the negative pressure difference across the aspiration (drainage) cannula. It is possible to predict the negative and positive pressures across each cannula size, for any given flow

It is possible to predict the maximum obtainable flow with negative pressures within the safety limits through graphs specific to each cannula (type and size), plotting the negative pressures against the flow rate. The same holds true for those drawn for the arterial side, where the pressure drop across the cannula is plotted related to the flow rate (Fig. 6.12). Thus, it can be known in advance which flow could be safely warranted according to cannulas dimensions.

6.4.4 ECMO Physiology: Oxygen Consumption and Delivery

Oxygen consumption (VO_2) depends on the basal metabolism which is regulated at the hypothalamic level and varies with age:

- Neonate 5–8 mL/kg/min.
- Child 4–6 mL/kg/min.
- Adult 3–5 mL/kg/min.

According to Fick's principle, oxygen uptake from the lungs equals the tissues consumption, thus it can be assumed that:

$VO_2 = CaO_2 - CvO_2$ (Formula 1)

CaO_2 = arterial content of oxygen

CvO_2 = venous content of oxygen

The content of oxygen in the blood (arterial or venous) is given by the following formula (2):

$$ContO_2 = \underbrace{(Hb\ g/dL \times SatO_2 \times 1.36\ mL/g)}_{Hb\ carried\ O_2} + \underbrace{(PO_2 \times 0.003\ mL/mmHg/100\ mL)}_{Dissolved\ O_2}$$

Most of the oxygen in the blood is carried linked to hemoglobin (Hb g/dL × $SatO_2$ × 1.36 mL/g), where 1.36 mL/g is the hemoglobin oxygen binding capacity. The amount of oxygen dissolved in blood is negligible and depends on the PaO_2 and the solubility coefficient of oxygen in the blood (0.003 mL/mmHg/100 mL). PO_2 does not reflect the true amount of oxygen carried in the blood, since it just determines the hemoglobin oxygen saturation and the amount of oxygen dissolved in the blood, without taking into account the hemoglobin concentration and the oxygen linked to hemoglobin. Hemoglobin concentration is the main determinant of oxygen transportation in blood.

e.g.: Hb 10 g/dL, $SatO_2$ 98%, PaO_2 100 mmHg: O_2 content 13.43 mL/dL.

Hb 15 g/dL, $SatO_2$ 85%, PaO_2 50 mmHg: O_2 content 17.49 mL/dL.

From the above example, it can be easily understood how the content of oxygen in the blood is greater with a hemoglobin concentration of 15 g/dL, even if the PaO_2 is halved.

The transport of oxygen to tissues (DO_2) depends on the cardiac output (CO) and the CaO_2, according to the following formula (3):

$DO_2 = CO \times CaO_2$

The relationship between DO_2 and VO_2 is shown in figure (Fig. 6.13). In normal conditions, the DO_2/VO_2 ratio is 5:1, corresponding to an oxygen extraction rate (O_2ER) from tissues of 20% (20–28% normal value). This ensures a high functional reserve, making oxygen consumption (VO_2) dependent on delivery (DO_2) only when the DO_2/VO_2 ratio is below 2:1. In such cases, metabolism becomes anaerobic, with tissue oxygen debt and the production of lactates (Fig. 6.13).

In the following calculations, we will not take into consideration the dissolved oxygen, given its very low contribution to oxygen transportation, and the Formula 2 can be simplified:

$ContO_2 = SatO_2 \times (Hb\ g/dL \times 1.36\ mL/g)$ (Formula 4)

Since the O_2ER is given by:

$O_2ER = CaO_2 - CvO_2/CaO_2$ (Formula 5).

Substituting for the arterial and venous $ContO_2$, the formula 5 can be rewritten as follows:

$O_2ER = [SaO_2 \times (Hb\ g/dL \times 1.36\ mL/g)] - [SvO_2 \times (Hb\ g/dL \times 1.36\ mL/g)] / [SaO_2 \times (Hb\ g/dL \times 1.36\ mL/g)]$ (Formula 6)

Thus:

$O_2ER = SaO_2 - SvO_2/SaO_2$ (Formula 7)

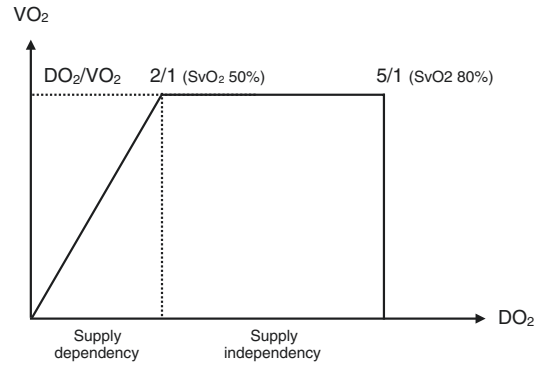

Fig. 6.13 Relationship between oxygen delivery (DO2) and oxygen consumption (VO_2). When the DO2/VO2 ratio falls below 2:1 (SvO_2 50%), VO_2 is dependent from DO_2 and metabolism becomes anaerobic with production of lactates

Formula 7 explains how the SvO_2, (n.v. 75–80%, O_2ER 4–5), is an indirect index of the relationship between DO_2 and VO_2. If there is an increase in metabolism, or the patient becomes anemic, the body can try to compensate through an increase in the cardiac output. If this compensation fails and the SvO_2 drops below 50% (O_2ER 2:1), the metabolism becomes anaerobic. ECMO can help in maintaining an appropriate DO_2 with different mechanisms, according to the ECMO configuration:

- Increase in the $ContO_2$ (VV-ECMO);
- Increase in the $ContO_2$ and support to the CO (VA-ECMO).

The production of CO_2 is given by the following formula:

$VCO_2 = CO \times (CaCO_2 - CvCO_2)$ (Formula 8)

Unfortunately, the calculation of the arterial and venous $ContCO_2$ is not possible and the VCO_2 is a directly measured value. $PaCO_2$ is proportional to VCO_2 and inversely proportional to alveolar ventilation.

$PaCO_2 = VCO_2/VA$ (Formula 9)

CO_2 removal is extremely effective on ECMO and is related to the "ventilation of the membrane lung" which is given by the flow rate of the sweep gas. In this way, ECMO can support or completely substitute the alveolar ventilation.

6.5 Starting an ECMO Run: Practical Aspects

6.5.1 Cannulas and Flows

Configuration, VV or VA, is chosen according to the needed support. VV-ECMO does not provide any direct cardiovascular support, although it is able to relieve cardiovascular instability due to mechanical ventilation and cardiopulmonary interactions.

The dimensions of the cannulas are critical to ensure adequate flows and are chosen to meet the predicted needed flows with no excessive negative (venous, ≥ -100 mmHg) and positive (arterial, $\leq$ 300 mmHg) pressures. Based on the age-dependent metabolic demands, the required minimum flows for cardiovascular support are:

- Newborn: 100 mL/kg
- Child: 75 mL/kg
- Adult: 50 mL/kg

An additional 20% has to be taken into account in VV-ECMO to overcome the flow wasted with recirculation. Based on the theoretically needed flows, it is possible to select the appropriate cannula size through specific Pressure/Flow charts (Fig. 6.12).

In neonates, infants, and toddlers, given the small dimensions of the femoral vessels, neck cannulation with double-lumen cannulas (VV-ECMO) or with the jugular-carotid approach (VA-ECMO) are the options of choice. Above 15 kg weight, the femoral approach is feasible, especially for VA-ECMO, while for VV-ECMO double-lumen cannulation is still preferable (single site cannulation, easier patients' mobilization/physical therapy, and reduction in the risk of infection).

The blood flow is regulated by setting the revolutions per minute (RPM), until the desired flow is reached, while monitoring the negative pressures, aiming at keeping them above −100 mmHg. The sweep gas is set at the same rate of the blood flow and adjusted to the desired $PaCO_2$. FiO_2 is kept at 1–0.9 on VV-ECMO (arterial-venous admixture in the RA), while on VA-ECMO it is regulated to the target PaO_2.

6.5.2 Oxygenator

The oxygenator (neonatal, pediatric, or adult) is chosen according to the size of the patient and to the predicted needed flows (Fig. 6.5).

6.5.2.1 Priming

Priming of the circuit can be done with balanced crystalloid solutions, which are adequate for adults and children. However, hemodilution and cardiovascular instability can occur after patients' connection to the circuit: volume expansion, blood transfusion, and inotropes/vasopressors administration might be needed. Some centers

add albumin to the priming solution, and this should be done carefully since albumin can cause the formation of foam and micro-bubbles inside the circuit. For neonates and infants, packed red blood cells (PRBCs) are usually added to the priming solution to reach a prime hematocrit of 35–40%. The circuit can also be primed with reconstituted blood by mixing PRBC with an adequate amount of fresh frozen plasma (FFP). Calcium is added to reverse the effect of citrate and heparin (1 unit/mL of priming) for anticoagulation (if FFP and/or PRBC are used). Before the initiation of extracorporeal life support (ECLS), the electrolytes status of the priming solution can be checked with a blood gas analysis.

6.5.2.2 Monitoring

Monitoring of the effectiveness of support is based on different principles in VV and VA-ECMO. Peripheral saturation is always above 90% on VA-ECMO, since fully saturated blood is pumped into the arterial circulation. Thus, the effectiveness of support is not indicated by high arterial oxygen saturation. Instead, the saturation of blood entering the circuit (mixed venous saturation) is proportional to the O_2 extraction rate from tissues (Formula 6). When this value is above 70–75%, the generated flows can guarantee an adequate DO_2, and VO_2 is independent of delivery (Fig. 6.13).

On VV-ECMO, the effectiveness of support is evaluated by the peripheral arterial saturation. Given the admixture of oxygenated and deoxygenated blood at the level of the RA (3/1 ratio), if there is little or no contribution to oxygenation from the lung, arterial saturation cannot be higher than 85%. A saturation of 85% is more than sufficient to meet the organism oxygenation needs.

6.5.2.3 Flow

With centrifugal pumps, it is mandatory to ensure continuous monitoring of the generated flow which, as explained previously, is not constant. Flow probes are placed on the arterial limb of the circuit (Fig. 6.1c).

6.5.2.4 Negative Aspiration Pressures

Negative aspiration pressures should not exceed −100 mmHg. An increase in the negative pressures (i.e., more negative) might indicate a hypovolemic patient or excessive RPM settings relative to the dimensions of the venous lumen/venous cannula.

6.5.2.5 Positive Pressures

Positive pressures are influenced by all the resistances placed downstream to the pump (Fig. 6.1b and c): oxygenator, circuit, arterial lumen/cannula, patient's vascular resistance. Positive pressures can be measured before and after the oxygenator. An increase in the pre-post oxygenator pressure difference is indicative of the health status of the membrane lung (clotting inside the oxygenator), thus giving indirect information on its performance.

6.5.2.6 Recirculation

Recirculation should always be suspected on VV-ECMO when the patient is desaturated, and there is a consistent increase in the saturation of the blood in the venous limb of the circuit.

6.5.2.7 Cannulation Technique

Cannulation can be performed surgically or percutaneously. With surgical cannulation, it is necessary to reconstruct the vessels at the time of decannulation, while, with the percutaneous approach, reconstruction is needed only for the artery. Surgical cannulation is reserved for smaller children (below 15 kg), especially for the veno-arterial configuration (jugular-carotid). Veno-venous percutaneous cannulation can be performed safely, even in neonates (double-lumen cannulation through the IJV), and does not require surgical repair at decannulation. In up to 80% of the double-lumen or double-lumen bicaval cannulations, the vessel remains patent at follow-up [4]. In the case of veno-arterial femoral cannulation, it is necessary to provide distal perfusion of the limb. This is achieved with a small infusion cannula (5–7 Fr introducer) inserted in the femoral artery, in proximity, but distal to the main cannulation site. The distal

perfusion cannula is connected to the arterial side of the circuit. Flow is obviously directed toward the foot.

6.5.2.8 Anticoagulation

Anticoagulation is needed to prevent clotting within the circuit and to avoid embolism to the patient. In special cases, it can be stopped to allow surgical interventions on ECMO or to control critical bleeding, provided that high flows are maintained and a spare circuit is readily available.

Anticoagulation is ensured most commonly with a continuous infusion of unfractionated heparin (20–70 U/kg/h). Infusion is titrated to an activated clotting time (ACT) of 140–200 s, with higher values on VA-ECMO. ACT is a point-of-care test exploring the whole blood (platelets and coagulation factors). At the time of cannulation or in case of insufficient anticoagulation, a bolus of heparin might be needed to reach rapidly the desired level of anticoagulation (25–100 U/kg). The aPTT (activated partial thromboplastin time) only measures the intrinsic pathway of coagulation and should be maintained 1.5–2 times the normal value. The heparin levels are reflected by the Anti-Xa activity in plasma, values of 0.3–0.7 IU/mL are indicative of an adequate heparin dose. Thromboelasto-graphy/metry can be useful in selected cases to study the coagulation cascade, platelet function, fibrinolysis, and heparinization. During an ECMO run the following values should be warranted:

- Antithrombin III: 70–120%
- Platelets: 80,000 cells/mm^3
- Fibrinogen: 250–300 mg/dL

In case of bleeding, coagulation factors and platelets should be replaced, heparin infusion can be reduced or stopped, tranexamic acid infusion can be taken into consideration (bolus 4 mg/kg, followed by a continuous infusion of 1 mg/kg/h), as well as activated recombinant factor VII administration (90 mcg/kg, life-threatening bleeding). A spare circuit should be immediately available in case of clotting.

If heparin-induced thrombocytopenia occurs, alternative anticoagulant drugs are Bivalirudin or Argatroban [5].

6.6 ECMO for Airway and Tracheal Surgery

Respiratory failure is a well-established indication for ECMO, a condition that can be often found in patients requiring airway or thoracic surgery (e.g., congenital diaphragmatic hernia, tracheal stenosis). ECMO can be taken into consideration during an EXIT (ex-utero intrapartum treatment) procedure for airway obstruction or malformation. Moreover, it is also extremely effective in supporting patients during tracheal surgery. If the tracheal stenosis is not associated with vascular or cardiac malformations, requiring simultaneous cardiac correction in CPB, tracheal surgery can be performed on ECMO. The surgical field is free from cannulas, with better visualization of the airway, sternotomy is limited to the manubrium, and bleeding is prevented since heparin infusion can be reduced (target ACT 140 s) or even stopped (Fig. 6.14). ECMO can be maintained after surgery allowing endo-

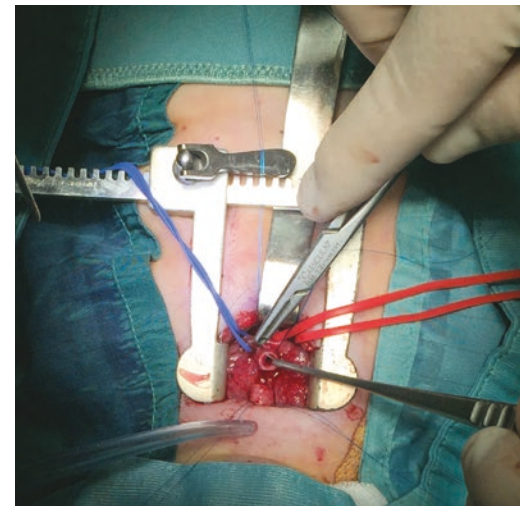

Fig. 6.14 Surgical field during slide tracheoplasty on ECMO. Note the absence of significant bleeding, the very limited sternotomy and the absence of cannulas

scopic controls or eventual treatments (balloon dilation and stent placement), with the safety given by complete control of oxygenation and CO_2 removal. With VV-ECMO and percutaneous cannulation, a minimally invasive approach to tracheal surgery can be performed even in neonates [6].

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Pulmonary Function Tests

7

Oliviero Sacco

7.1 Spirometry

Spirometry is the procedure that measures the rate of changing lung volumes during breathing maneuvers. Specifically, it measures the amount (volume) and speed (flow) of air that can be inhaled and exhaled by the patient. It can be used to diagnose and monitor patients with a variety of respiratory diseases and to measure the respiratory function of a patient before and after a surgical procedure. For this practical reason, both anesthesiologists and surgeons must be able to interpret the spirometry results in the general clinical contest of the patient.

A variety of spirometers are available on the market, and the equipment must fulfill the American Thoracic Society/European Respiratory Society (ATS/ERS) recommendations for spirometry [1]. The recent electronic spirometers calculate the percentage of the predicted normal values based on reference values, according to the patient data: weight and height, age, sex, and race.

Many newer generation spirometers do not require calibration daily as used to be the case decades ago. The respiratory technician or the physician performing the spirometry tests requires training to perform the examination correctly.

O. Sacco (✉)
Pediatric Pneumology and Respiratory Endoscopy Unit, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: olivierosacco@gaslini.org

It is possible to perform reliable spirometry tests even in preschool noncollaborating children. Other methods have been developed to assess lung function in infants and young children: the interrupter technique, the forced oscillation technique, the gas washout techniques, the tidal breathing techniques, and the rapid thoracoabdominal compression maneuver [2]. These maneuvers are usually performed in advanced respiratory laboratories and will be not discussed in this chapter.

7.2 Indications and Contraindications to Spirometry

Spirometry is indicated for children with recurrent wheezing/bronchial hyperreactivity, chronic cough, and for the diagnosis and management of asthma and cystic fibrosis. It is also used to measure lung involvement in systemic diseases that can affect the lungs as hematooncology conditions and connective tissue disorders. Spirometry is helpful in ascertaining preoperative lung function in chest deformities, such as pectus excavatum, scoliosis, and neuromuscular diseases, muscular dystrophy, and cerebral palsy. It is an essential test to evaluate the preoperative risk before general anesthesia, particularly for cardiothoracic surgery, so that both anesthesiologists and surgeons must be

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_7

familiar with its interpretation and the consequent clinical indications.

No absolute contraindications are recognized for spirometry, and relative contraindications are acute respiratory tract infection, recurrent/subcontinuous cough, hemoptysis, pneumothorax and pneumomediastinum, aneurysm, uncontrolled hypertension, recent thoracic, abdominal or eye surgery, nausea, vomiting or pain, confusion, or dementia.

7.2.1 Performing the Spirometry Test

The patient's weight and height have to be obtained and entered into the spirometry software along with the personal data: name, age, sex, race, and ID. The patient position for the test may be sitting or standing. A disposable mouthpiece is attached to the spirometer, and a nose clip is used to pinch the nose to avoid loose part of the blow through the nose. The FVC maneuver is the most useful and usually is the only one performed and the only one described for the scope of this chapter.

7.2.2 FVC Test Maneuver

The patient must take two to three tidal breaths with the lips sealed tightly around the mouthpiece and the nose closed by a clip; then, he/she is asked to take a deep breath and then blow air through the mouthpiece suddenly and as fast as possible and to continue to blow for as long as possible (preferably at least 6 seconds) until no air is left to exhale. The test should be repeated at least three times and checked for acceptability and repeatability as shown below. If the results are not acceptable, the test may be repeated another 4–5 times before abandoning the attempt.

In our experience, about 50% of the children aged 4–5 years are able to perform technically acceptable and reproducible spirometry maneuvers, and the percentage increases gradually with age: 90% of neurologically normal children aged 7–8 years are capable to perform reproducible pulmonary function test. During the test, at any age, it is essential to ensure that the child is cooperative and follows the instructions.

The technician/physician performing the test has to be careful that: the lips are tight around the mouthpiece (not obstructed by the tongue) and the nose clip is in position, the inhalation is complete, the exhalation start is fast and forceful without pause or cough, and the blow is continued until exhaustion, as suggested by a plateau on the volume-time curve (Fig. 7.1b) [3]. The plateau at the end of the expiratory phase of spirometry is generally absent in preschool children. In these patients, the presence of the plateau at the end of the FVC curve is no more a necessary criterion for evaluating a satisfactory expiration: a flow–volume curve demonstrating a rapid rise in the peak flow and a smooth descending limb is acceptable in these patients (Fig. 7.2), particularly if the FVC maneuver is reproducible in at least twice.

7.2.3 Rating the Spirometry Results

There are different steps to be considered in the following order:

Assessing the tests for acceptability and repeatability. First of all, errors or artifacts in performing the spirometry procedure can be detected simply by looking at the shape of the spirometry graphs. The errors may include poor effort and cough, mouthpiece partially obstructed by the tongue, hesitation in blowing the air, premature finish of the effort with an abrupt stop of expiration, and premature finish and restart with more than one breathing attempt. Two types of graphs are produced in spirometry: flow–volume curve (Fig. 7.1a) and volume–time curve (Fig. 7.1b). Both are used, but the most important and used in evaluating the spirometry is the flow–volume curve, especially in the expiratory part of the FVC maneuver (see subsequently). A spirogram is acceptable if it is free from errors or artifacts with a good start and a satisfactory expiration in accordance with ATS/ERS standards [1]. Some modifications in the criteria have been suggested in an ATS/ERS statement regarding preschool children [1, 4]. In these patients, as described

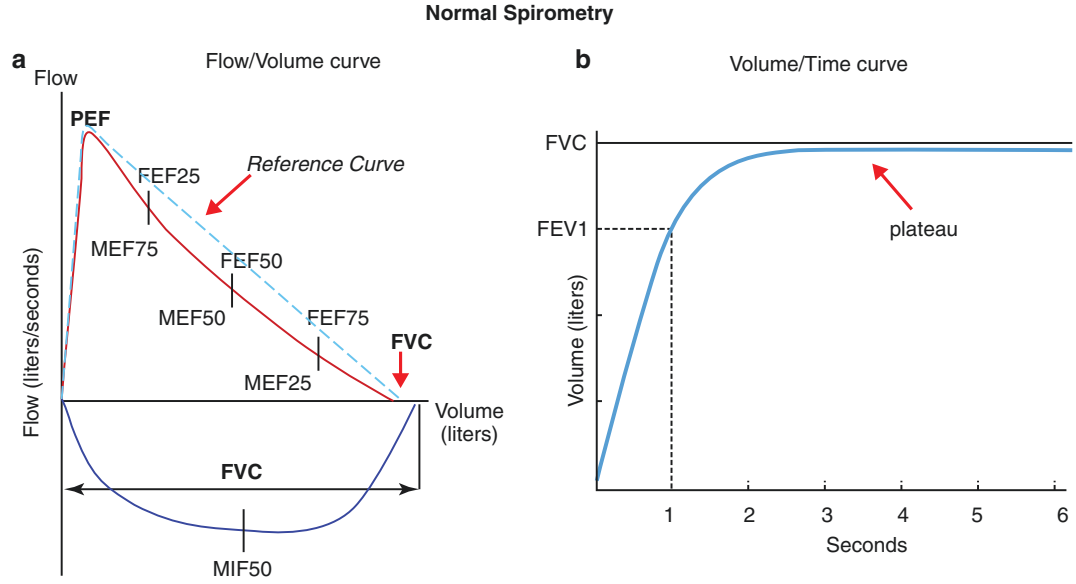

Fig. 7.1 Normal spirometry curve: (**a**) Flow/volume curve and (**b**) Volume/time curve

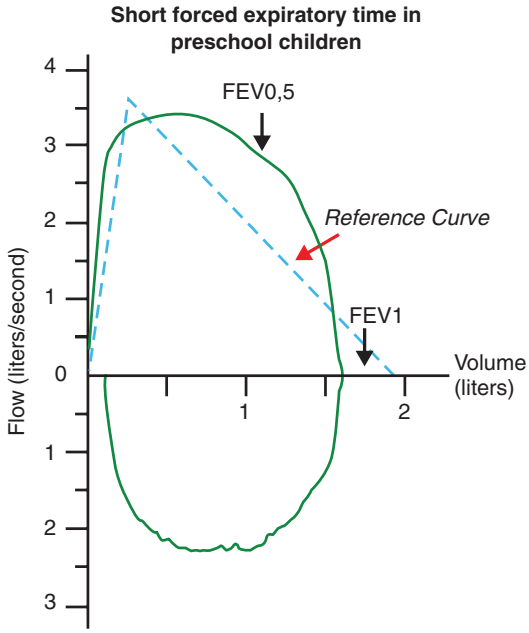

Fig. 7.2 Bell-shaped flow/volume curve in preschool children due to short forced expiratory time in preschool children

before, the presence of the plateau at the end of the FVC curve is no more a necessary criterion for evaluating a satisfactory expiration: A flow–volume curve demonstrating a rapid rise of the peak flow and a smooth descending limb is acceptable (Fig. 7.2). Two acceptable spirograms are sufficient for this age, while for school-age children a minimum of three satisfactory spirograms is generally required to be sure about the test reproducibility.

1. Identify the parameters to evaluate the spirometry results (Fig. 1a and b). The most used parameters are:
   (a) FVC (forced vital capacity): following a maximal inhalation, it is the total amount of air exhaled forcefully.
   (b) FEV1 (forced expiratory volume in 1 second): following a maximal inhalation, it is the amount of air exhaled in the first second. Preschool children have a short forced expiratory time; therefore FEV0.5 and FEV0.75 (second) may be used in preschool children (Fig. 7.2).
   (c) FEV1/FVC ratio is the most used indicator for identifying airway obstruction but not the most reliable, particularly in children, because it is strictly dependent on the expiratory effort expressed by the patient, and the effort is directly correlated to the patient's age.
   (d) FEF25–75% or MEF50 (flow over the middle half of the FVC: from 25% to 75% of the FVC during forced expiration). It is

a sensitive index of airflow obstruction because it is less dependent than FEV1/FVC ratio to the expiratory effort and it is therefore particularly useful in children. The ERS Global Lung Function Initiative has published the global multi-ethnic lung function for spirometry for the 3- to 95-year age range [5]. The comparison is expressed as a percentage of the predicted value or below the lower limit of normal (<90% confidence limit).

2. Identifying the spirometry pattern (normal, obstructive, restrictive, or mixed).

Abnormalities in a spirometry test can be identified first of all by looking at the shape/morphology of the curve and then comparing the test values with the patient's reference values (Figs. 7.1a, b, and 7.3).

(a) A normal flow–volume curve has a shape like a sail rising very sharply toward the peak (Peak Expiratory Flow or PEF) and then descending shortly with a straight line at an angle of about 45° toward the end, the plateau (Fig. 7.3). Normal preschool children have smaller lung volume compared to rapid emptying of the airways: the result is a convex shape of the flow-volume expiratory curve after the PEF (Fig. 7.2). The expiratory shape becomes more linear (similar to adult PFT) as the child grows in school age. Normal values for FVC and FEV1 are considered >80% of predicted or above the lower limit of normal (Fig. 7.1a, b).

(b) An obstructive flow–volume curve shows a good rise toward the PEF followed by a concave expiratory curve, indicating that the decrease in the expiratory flow is faster than the decrease in lung volume during the expiratory phase. It is usually characterized by decreased FEV1 (<80% of predicted or below the lower limit of normal), decreased FEV1/FVC, and normal FVC (Fig. 7.3). To determine if the FEF1/FVC ratio is low, indicating an obstructive defect in patients five to 18 years of age, the National Asthma Education and Prevention Program guideline says that a ratio of less than 85% is consistent with an obstructive defect as long as the patient has symptoms consistent with obstructive lung disease [6]. The FVC may be decreased even in case of severe obstruction, the expiratory curve is elongated and thin toward the end as a rat's tail without a definite plateau (Fig. 7.3). FEF25–75% values below 60% of predicted also suggest an obstructive pattern. FEF25–75% or MEF50 (Fig. 7.1a), being mid expiratory flow, is less effort dependent than FEV1as explained before, it is considered a measurement of small airway patency, particularly useful in children with asthma [7].

(c) A restrictive flow-volume curve is characterized by an expiratory line sharply descending toward the end with a consequent low FVC value, that is the distinctive/predominant pattern, with a normal or decreased FEV1 that can have the same value as the FVC (Fig. 7.3). The FEV1/FVC is consequently increased toward the value of 1 due to the low FVC value. It is very important at the moment of the spirometry procedure to keep in mind that a poor effort by the patient can falsely mimic the restrictive curve with a proportionate reduction in both FEV1 and FVC.

(d) A mixed flow—volume pattern has a decreased value of all three values: FEV1,

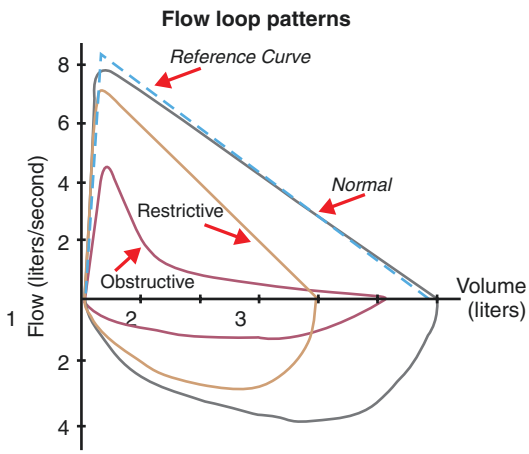

Fig. 7.3 Flow loop patterns in normal, obstructive, restrictive adn miwed flow-volume curves

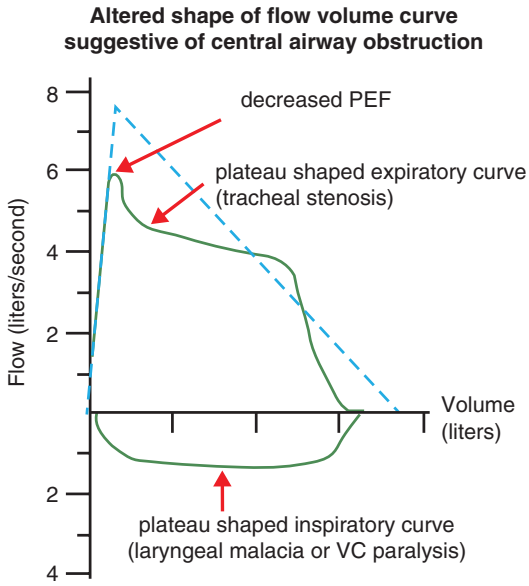

Fig. 7.4 Altered shape of flow-volume curve suggestive of central airway obstruction due tracheal stenosis (expiratory curve) or laryngeal pathology (inspiratory curve)

FVC, and FEV1/FVC and is common in severe bronchospasm/asthma.

(e) An altered shape of flow–volume curve can be suggestive of central airway obstruction (larynx or trachea) (Fig. 7.4). Normal expiratory flow with a plateau-shaped inspiratory curve is suggestive of collapsible extra thoracic airway obstruction (e.g., laryngeal malacia or paralysis). On the contrary, normal inspiratory flow with a decreased maximal expiratory flow (PEF) and a box-shaped expiratory curve suggest collapsible major intrathoracic airway obstruction (e.g., vascular ring or extrinsic compression plus tracheomalacia as is quite common in esophageal atresia and tracheoesophageal fistula). If both inspiratory and expiratory flows are decreased, a severe, fixed intrathoracic, or extrathoracic airway obstruction is likely present.

7.2.4 Bronchodilator Response

The bronchodilator response (BDR) test is useful to assess reversibility of the obstructive pattern in spirometry, which is characteristic of asthma or

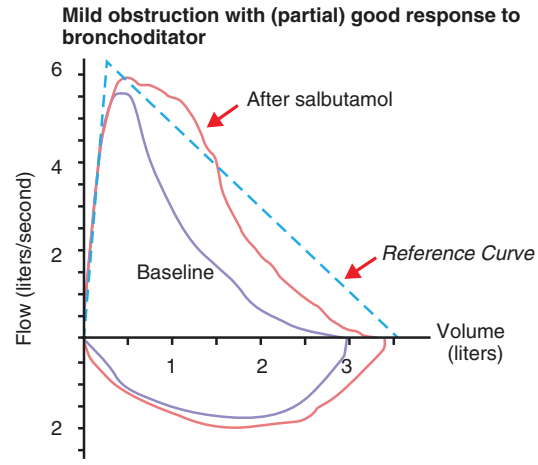

Fig. 7.5 Bronchodilator response in flow-volume obstructive pattern to short-acting β2 agonist: salbutamol

bronchial/airway hyperreactivity. A baseline spirometry is performed in patients free of any kind of bronchodilator therapy: in the last 6 or 12 h, respectively, for short- and long-acting β2 agonist. A second spirometry is then performed after 10–15 min of 2–3 doses of 100 μg salbutamol spray, delivered by a metered dose inhaler (MDI) with a spacer. For a positive response to the bronchodilator, the thresholds considered significant are an improvement >12% in FEV1 or 15–25% in FEF25–75% in the post-salbutamol test and suggest reversibility of airway obstruction (Fig. 7.5) [8]. However, it is important to underline that the presence of airway obstruction in the spirometry without a significant BDR does not exclude the diagnosis of asthma because it can be the expression of a chronic inflammation condition of the bronchial wall not responsive to the β2agonist/salbutamol, due to poorly controlled asthma in children. These patients probably need a course of topic or oral corticosteroid before the test can be repeated. On the other hand, a negative BDR on a singular test does not exclude the diagnosis of bronchial hyperreactivity or asthma, clinical conditions characterized by a variable bronchoconstriction state and mutable clinical history, particularly in the pediatric age. A methacholine challenge test can be indicated in these patients to diagnose bronchial hyperreactivity.

Similarly, a baseline spirometry within normal ranges but followed by a BDR with a significant increase in the expiratory flow should

be interpreted in these patients only as an expression of bronchial hyperreactivity, a clinical condition characterized by frequent bronchospasm episodes, mainly correlated with the recurrent viral infection characteristic of pediatric patients [9]. These considerations suggest that BDR may be a useful objective tool to assess the presence of a bronchoconstriction tone, particularly in children with bronchial hyperreactivity, and can suggest the prescription of maintenance therapy with bronchial anti-inflammatory drugs.

7.2.5 Methacholine Challenge Test (MCT)

In this test, also known as bronchoprovocation test, increasing doses of methacholine are delivered to the patient so as to achieve bronchoconstriction: the opposite effect of the BDR. Methacholine mimics the neurotransmitter acetylcholine to directly interact with muscarinic receptors on airway smooth muscle, resulting in airway narrowing and decreased expiratory flows. The test is indicated when the baseline spirometry is within the normal limits, the BDR is without significance, and the diagnosis of bronchial hyperreactivity/asthma is suspected on clinical records.

The patient has to be out of every medication for at least 1 week for inhaled corticosteroids and antileukotrienes and 6–36 h for short and long bronchodilators prescribed in pediatric age [10]. After a baseline spirometry test, the methacholine challenge can start only if the FEV1 is at least >60% of the predicted value [10]. The test starts with a very small dose of methacholine (<0.25 mg/mL), then the doses are progressively increased, and after every dosage an FCV is performed. The test has to be interrupted when, compared with the baseline value, a 20% decrease in FEV1 is recorded. The smaller the methacholine dose necessary to cause a 20% decrease of FEV2, the higher the degree of airway hyperreactivity. The PC_2O is the provocative concentration (methacholine mg/mL) causing a 20% fall in FEV1, and the PD20 is the provocative dose causing a 20% fall in FEV1 (extrapolated by the last two PC20 delivered to the patient), according to the new recommendations [10]. The Airway hyperresponsiveness (AHR) is rated as normal, borderline, mild, moderate, and severe, according to the PD20 values (Table 7.1).

Table 7.1 Airway hyperresponsiveness degrees according to the response to methacholine

Categorization of airway response to methacholine		
PD20 mg/mL	PC20 μmol (μg)	Airway hyperresponsiveness (AHR)
>2 (>400)	16	Normal
0.5–2.0 (100–400)	4–16	Borderline AHR
0.13–0.5 (25–100)	1–4	Mild AHR
0.03–0.13 (6–25)	0.25–1	Moderate AHR
<0.03 (<6)	<0.25	Severe AHR

The MCT is highly sensitive for diagnosing airway hyperreactivity/asthma; however, its low specificity results in false-positive results; on the other hand, a negative test means that a diagnosis of bronchial hyperreactivity/asthma is unlikely.

7.3 Conclusions

Spirometry is a fundamental test in the diagnosis of lung disease in pediatric age and, with the availability of better equipment with incentives for children, even preschool patients can perform acceptable/reproducible spirometry. There has been much progress over the past decade regarding the standardization of spirometry, which includes differences recognized between spirometry performed by children and adults. Therefore, there is no more excuse to underuse spirometry in pediatric age, and there is a need to encourage its use by all the pediatricians treating children with respiratory diseases to monitor disease and response to therapy. The various measurements obtained from spirometry with the ancillary tests as the BDR and the MCT test can be very useful even in evaluating the patients before a surgical procedure to avoid the

occurrence of respiratory failure due to intraoperative bronchospasm or to an underdiagnosed baseline poor respiratory function.

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Part III

Chest Wall

Pectus Excavatum

8

Michele Torre and Federico Palo

8.1 Introduction

Pectus excavatum (PE) is a relatively common thoracic malformation, prevalence is 1 on 300–1000 people, represents 90% of thoracic malformation in pediatric age, is characterized by a depression of the sternum which appears during pediatric age, and becomes more severe over the years [1–4]. This malformation involves the sternum and the costal cartilages, but it is not clear if the primary malformation involves first one then the other. Male sex is more frequently affected than female [5–7].

8.2 Classification

PE is characterized by different grades of severity which need different diagnostic and therapeutic approaches [8]. Different types of PE are described from more localized forms, defined as "punch shape" or "cup shape," to less localized forms, such as "saucer shape" up to severe forms like "grand-canyon shape" or mixed forms like "Currarino Silverman" [9] (Fig. 8.1).

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

Other important aspects of the malformation are the symmetry, the length, the depth, and the torsion of the sternum.

Sex and age of the patients seem not involved in the distribution of the different types of PE [10].

8.3 Diagnosis

Prenatal diagnosis is possible but it is very rare [11, 12]. Diagnosis of pectus excavatum is made by physical examination. On visual examination, the patients not only have an obvious depression of the anterior chest wall but also, they have a typical aspect, they are tall and slim with rounded shoulders and protuberant abdomen ("pot-belly"). Many of them usually have other deformities, such as scoliosis, but only a third of these patients require surgical treatment [13]. Many patients, in particular the ones that are tall and thin, suggest a connective tissue disorder. About 20% of patients show physical signs of Marfan syndrome and 2% of Ehlers-Danlos syndrome [14, 15] Palpation is helpful to determine cardiac displacement and sternal torsion. Cardiac auscultation can be useful to identify associated cardiopathy, the most frequent one is secondary to mitral valve collapse [16, 17].

Determining the location and depth of the deepest part of the depression is helpful in planning surgical correction. Depth can be measured

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_8

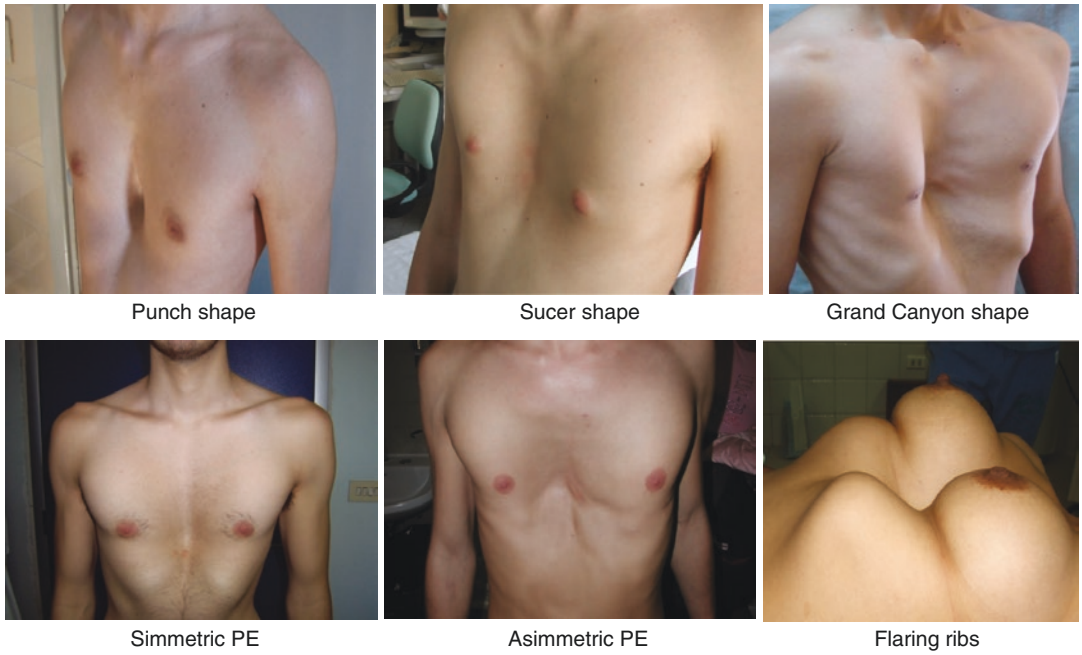

Fig. 8.1 Different types of Pectus excavatum

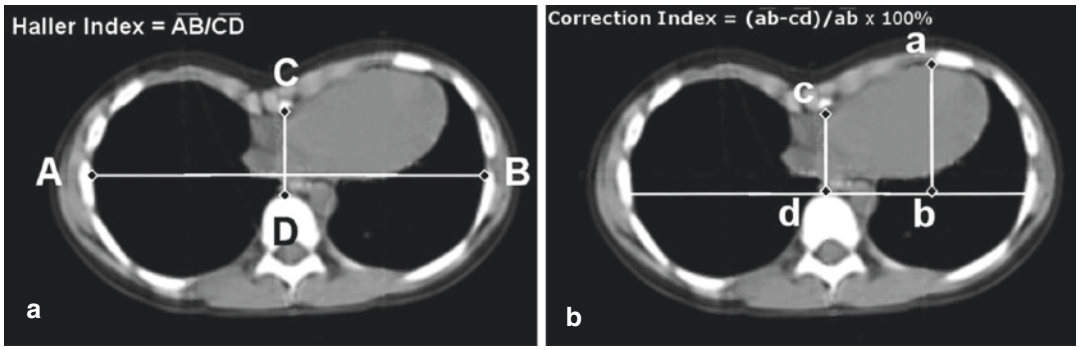

Fig. 8.2 (**a**) Haller index (**b**) Pectus correction index

with different instruments, but the most important measurements are the Haller index (HI) and the pectus correction index (PCI) (Fig. 8.2), both calculated after performing a TC scan or an MRI scan [18].

HI is the division between lateral and anteroposterior diameter measured in the deepest point [19]. This index is widely accepted, and if the index is higher than 3 or 3.25, it is suggestive for surgical correction [18–20]. In most cases, the deepest point is at the xiphoid of the sternum. If the deepest point is not in the midline, there is an asymmetric type of pectus excavatum; more frequently, the right side is the more affected by this asymmetry and can be confused with the Poland syndrome [21].

PCI was recently introduced as an evolution of Haller index and requires drawing a horizontal line across the anterior spine. Then two distances are measured: the minimum distance between the posterior sternum and the anterior spine as is used for the HI and the maximum distance between the line placed on the anterior spine and the inner margin of the most anterior

portion of the chest. The difference between the two lines is simply the amount of defect the patient has in their chest. If this difference between the measurements is then divided by the maximum prominence of the chest (the longest measurement) and multiplied by 100, it generates the percentage of chest depth the patient is missing centrally [22].

The costal cartilages inferior to the sternum are sometimes "flared," that is, they protrude anteriorly in the upper abdomen inferior to the depression.

Before surgical treatment, it is important to assess other symptoms of the patients; in fact, many of them have exercise intolerance (64.5%), chest pain during exercise (51%), and easy fatigability during exercise (62.7%) and at rest (32%) [23] (Table 8.1).

Due to all these aspects, it is important to perform static and dynamic, if possible, pulmonary function tests, cardiology check with echocardiography, and ECG to exclude other coexistent pathologies.

Also, allergy tests are performed to exclude the presence of allergy to the metals of which the bar is made. From 10% to 15% is the incidence of nickel allergy in the population, and sometimes the allergy tests are negative. If an allergic reaction is diagnosed after the positioning, the treatment is based on low-dose steroid until the resolution of the symptoms, but sometimes this complication can cause the bar removal [24].

Table 8.1 Principal condition associated with PE [23]

Condition	Number	%
Exercise intolerance	211	64.5
Lack of endurance	205	62.7
Shortness of breath	203	62.1
Chest pain with exercise	167	51.1
Family history of PE	140	42.8
Chest pain without exercise	104	31.8
Asthma	70	21.4
Scoliosis	69	21.1
Heart problem	65	19.9
Frequent or prolonged URI	44	13.5
Palpitations	37	11.3
Pneumonia	28	8.6
Fainting/dizziness	27	8.3
Marfans syndrome	15	4.6
Family history of PE	13	4.0
Ehler-Danlos	9	2.8
Family history of Marfans	8	2.4

After all examinations, the patients are selected for the surgical correction if they meet at least two of the following criteria: [25–29].

- Haller index >3.25.
- Symptoms (cardiologic, pulmonary, or psychological).
- Cardiac compression with or without consequent cardiac disease.
- Compression of the vena cava or pulmonary veins.
- Significant restrictive disease on pulmonary function studies.
- Paradoxical movement of the chest wall.
- History of evolution.
- Severe disturbance of body image.

8.4 Treatment

Based on the severity of the malformation, the treatment could be conservative or surgical. The decision of the treatment is made in accordance with the patient and his family. It is widely accepted that the surgical correction must be done before the complete ossification of the thorax [26–30].

The choice is made taking into account the age of the patient, the severity, and associated symptoms.

The conservative management, when applicable, is performed by using a vacuum bell (also called Klobe's vacuum bell) patented in Germany and indicated in mild cases or severe cases before surgical operation. The application of this device has been demonstrated to reduce the thoracic wall defect [31–35].

The first surgical approach was described in 1949 by Ravitch; in this procedure, all deformed costal cartilages are resected preserving the perichondrium [25, 37–40].

Across the years, this procedure underwent some modifications, becoming less extensive in terms of cartilage resection to prevent asphyxiating thoracic chondrodystrophy [27, 36].

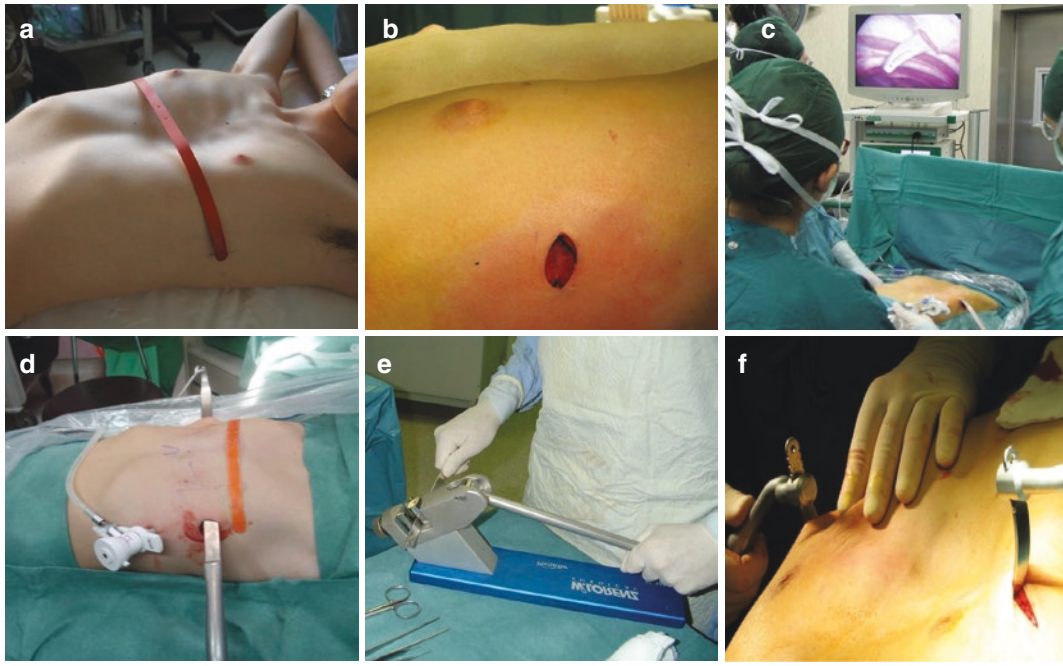

Fig. 8.3 The different stages of the surgical procedure as described by Donald Nuss: (**a**) bar measurement; (**b** and **c**) incision of the skin and thoracoscopic phase for the creation of retrosternal space; (**d**) chest wall stretching; (**e**) bar modeling; and (**f**) bar positioning, rotation, and stabilization

In 1970, another surgeon, Wada, performed a completely different approach; in fact, the concept of the operation was to remove completely the sternum and rotate it by 180° and sutured back to the ribs.

In 1997, a revolutionary approach (Minimally invasive repair of Pectus excavatum, MIRPE) was described by Donald Nuss, and his procedure was completely innovative because didn't include any resection of cartilages or bones. The operation involves implanting a retrosternal metallic bar that is bent according to the chest wall deformity of the patient and rotated at 180° to obtain an immediate correction of the defect. The procedure is made in thoracoscopy with three (sometimes more if is needed to implant more than one bar) small access on the side of the thorax (two on the right side and one on the left), and under vision a space between the heart and the sternum is created to allow the positioning of the bar through that space (Fig. 8.3) [25, 26, 31, 41].

The bars that were positioned are removed after a period of 2 or 4 years, usually 3 years.

8.5 Conclusion

The complication rate for all the types of procedures is low and without any significant difference between them [42, 43].

According to many studies, the complications can be divided into two groups, early complications, within the month, and late complications, after 30 days [23, 26, 30, 42, 44, 45].

The main early complications for MIRPE procedure (within 1 month) are spontaneous resolution pneumothorax (64.7%), pneumothorax that requires drainage (4–7%), transitory Horner syndrome (caused by epidural analgesia) (16%), wound infection (1.2–2%), pneumonia (less than 1%), pericarditis (0.5%) and pleural effusion (0.3–0.9%).

Late complications (after 1 month) are bar dislocation (1–7%), overcorrection (2–3%), allergic reaction to the metal of the bar (3%), severe wound infection (1.5%), pericardic effusion and pericarditis (0.5–1,5%), and persistence of pectus excavatum (1%).

Intraoperative complications are not common, but they can be very dangerous, such as cardiac opening, aorta lesion, lung lesion, pneumothorax, major bleeding [46–48].

Some studies demonstrate that the complications are correlated with the severity of the PE and on the surgeons' experience [45, 48].

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Pectus Carinatum

9

Michele Torre and Federico Palo

9.1 Introduction

Pectus carinatum, also called "pigeon chest," is a congenital deformation of the anterior chest wall, and it is characterized by an outward protrusion of the sternum [1].

It is the second most common anterior chest wall deformity; incidence is about 5–22% of all anterior chest wall deformities and is less frequent than pectus excavatum. Males have an incidence two to four times greater than females [2, 3].

Brodkin in 1949 recognized and described two separate types of protruding chest deformities, the chondrogladiolar and the chondromanubrial shape of the anterior thoracic wall [4].

9.2 Classification

Although the typical appearance of patients with pectus carinatum is characterized by a symmetrical protrusion of the sternum, some particular variants have been described [5–9]. The deformity can be symmetric or unilateral, with a rightward tilt of the sternum the more common unilateral condition [10].

The most common is the chondro-gladiolar (Fig. 9.1) variant also known as "chicken breast": 90° forward angle between the xiphoid process and the lower part of the sternum causes the protrusion of the body of the sternum, the maximum prominence is at the sterno-xiphoid junction.

The costo-manubrial (Fig. 9.2) variant also known as pectus arcuatum is a protrusion of manubriosternal junction and the adjacent ribs. The xiphoid process is contiguous to the end of the sternum in the sternal axis without angulation.

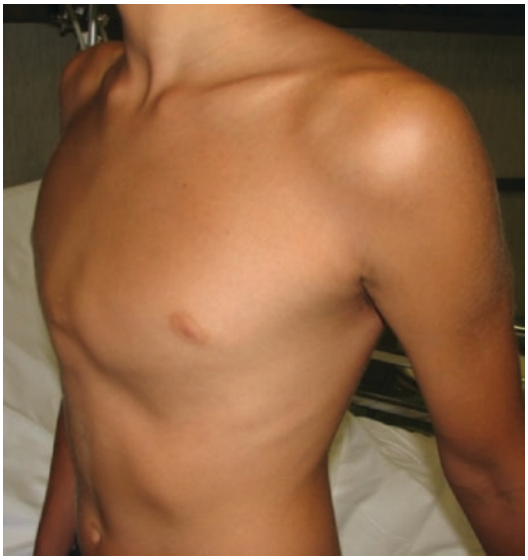

Fig. 9.1 Chondro-gladiolar

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_9

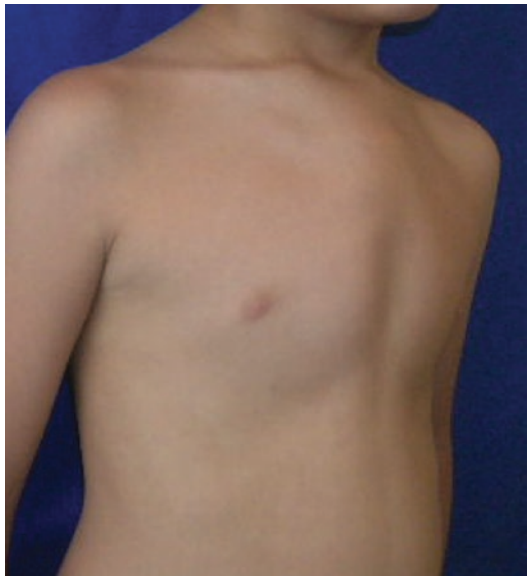

Fig. 9.2 Costo-manubrial

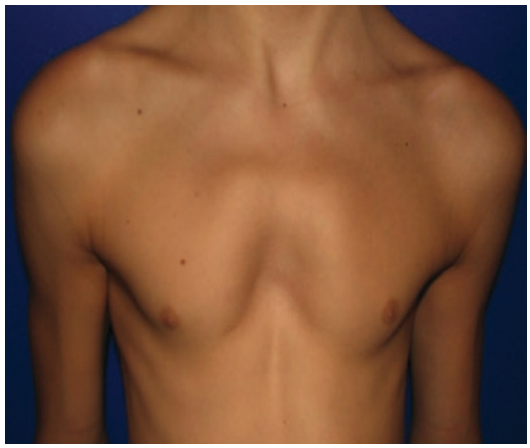

Fig. 9.3 Currarino Silverman

A particular form of costomanubrial variant is the Currarino-Silverman syndrome (Fig. 9.3), also called Pouter pigeon breast [11]. This malformation is characterized by premature fusion and ossification of the manubriosternal joint and sternal segments. This results in a superior symmetric carinatum chest deformity with a short thick sternum excavated in the lower third.

Some authors believe that this form, included in the classification of the pectus carinatum, must belong to the anomalies of fusion of the sternum, since the anomaly arises from a defect of the latter [12].

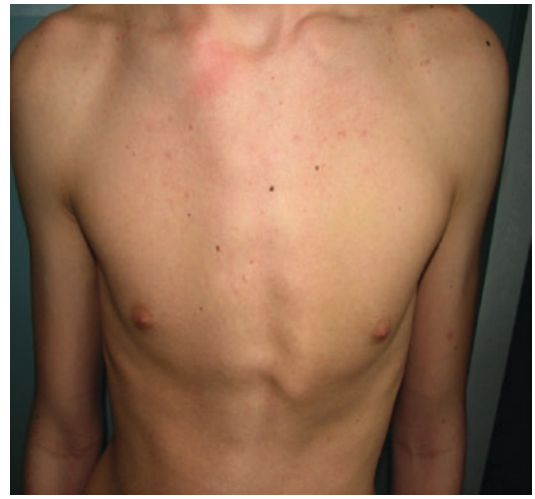

Fig. 9.4 Lateral PC

Lateral pectus carinatum (Fig. 9.4): unilateral prominence of elongated costal cartilages with concomitant tilting of the sternum toward the opposite side in various angles. This is the asymmetrical type.

Reactive PC [13] is a complication of PE correction. It is more frequent in patients with connective tissue disorders.

9.3 Diagnosis

Unlike other thoracic malformations, especially of pectus excavatum, the diagnosis of pectus carinatum occurs after adolescence [14].

Patients do not have characteristic symptomatology; they are often asymptomatic and in some cases, the diagnosis is made because the patient requires an evaluation for an aesthetic problem. The symptomatology occurs only in the most severe cases characterized by respiratory problems and less tolerance to physical exercise [8].

Diagnosis is made after clinical evaluation of the patient, computed tomography (CT), or lateral chest X-ray are performed to have more information, and also to evaluate the severity of the deformity, the Haller index (the ratio of the

transverse diameter of the chest wall to the greatest anteroposterior diameter) is used to grading the severity of the malformation [9].

9.4 Treatment

As for PE, Ravitch in 1952 described the first surgical technique for PC that consisted of a sternal osteotomy (Fig. 9.5). Recently, in an attempt to reduce the invasiveness of the procedure, some modifications were proposed [15, 16].

In 1992 was proposed the orthotic brace system. Based on the idea that applying a pressure upon the thorax of the patient, thanks to its malleability, allowed the correction of the defect. This approach cannot be used in adults due to the ossification of the thorax, so it can be applied only to adolescent patients [17]. Martinez-Ferro et al. have developed a bracing system that allows measurement of the pressure necessary for initial correction; it is called dynamic compression system (DCS) (Fig. 9.6). Due to changes in chest wall compliance with age, they found that older children required a greater pressure and duration of bracing to achieve satisfactory correction. The limits of this conservative treatment are, as said before, the age of the patient and its compliance, a significant proportion of patients (13.8%) abandoned treatment [18].

Abramson's procedure (Fig. 9.7) consists of an intrathoracic compression of the sternum by using a metal bar placed surgically in the presternal space through two lateral incisions under the pectoralis muscles and fixed to lateral stabilizers; the bar is usually removed after 2 years [19]. The result is immediate, and there is no need to wear an external brace every day. The results in patients treated with Abramson's technique at 5 years were good [20] (Fig. 9.8).

Recently, different thoracoscopic approaches for the correction of pectus carinatum were described. Thoracoscopic cartilage resection consists of cutting the anomalous costal cartilages of one or both sides preserving the internal thoracic vessels and nerves, and it can be associated with the Abramson procedure to better stabilize the sternum [21].

Thoracoscopic complete cartilage resection with perichondrium preservation (CCRPP) has been reported by our research team. It is different from the procedures described above because cartilages are isolated laterally and medially to the internal thoracic vessels, up to the chondrosternal joints. Internal thoracic vessels are coagulated and cartilages excised completely, leaving the anterior perichondrium intact [22].

Another minimally invasive approach consists of a submuscular dissection of the pectoralis muscle using CO_2. After that, a resection of the

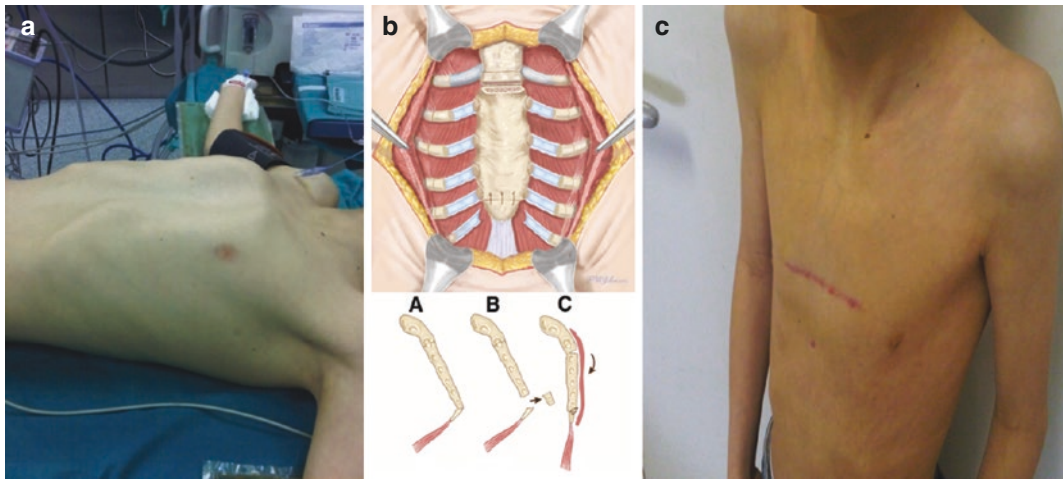

Fig. 9.5 Ravitch's technique for PC: (**a**) preoperative (**b**) surgical technique [2] (**c**) postoperative results

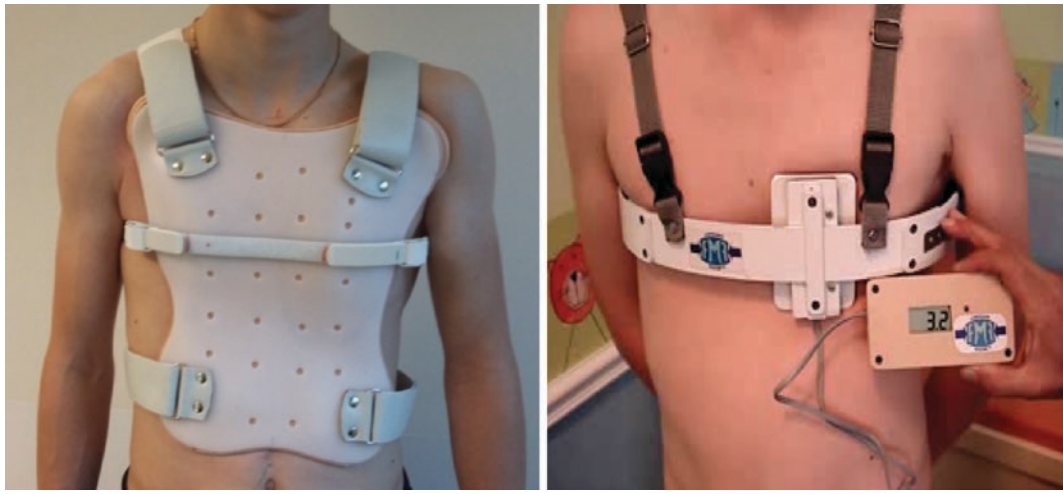

Fig. 9.6 DCS developed by Martinez—Ferro et al.

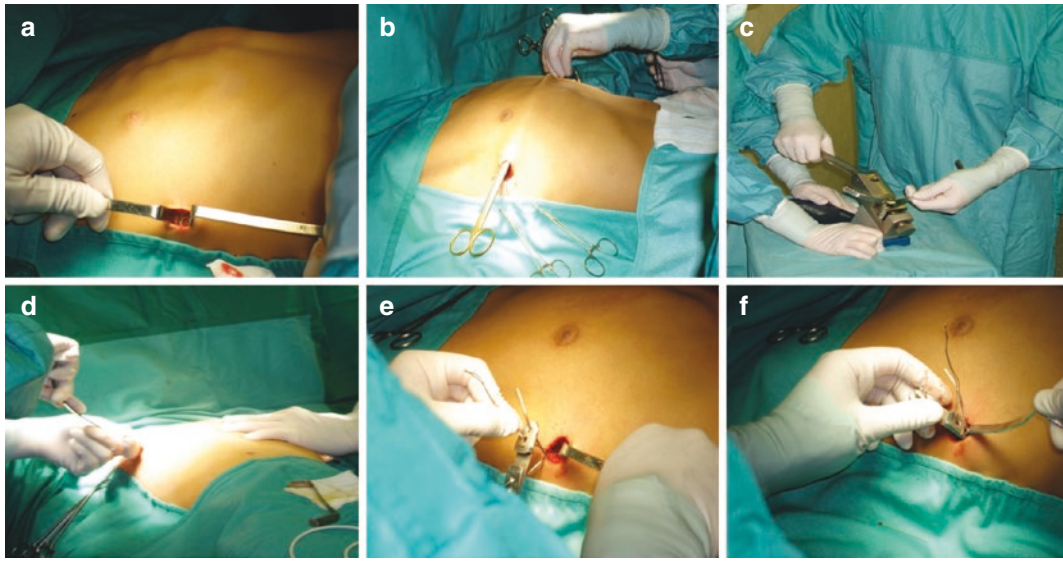

Fig. 9.7 Abramson's technique: (**a** and **b**) creating presternal space for the metal bar. (**c**) bar modeling. (**d**) bar positioning. (**e**, **f**) stabilization of the bar with stabilizers

ribs, sternal osteotomy, and insertion of the metal bar are performed through two lateral incisions between the anterior and the middle axillary lines. However, special eight-hole stabilizers are required [23].

Reactive PC after the Nuss procedure can be corrected by withdrawing the bar. An open procedure is advised only in the case of failure or in other cases. Alternatively, a minimally invasive procedure can be attempted.

9.5 Conclusions

In contrast to patients with pectus excavatum, the prognosis of patients with pectus carinatum is excellent. Most of these patients do not have characteristic symptomatology, and they often turn to the surgeon for an exclusively aesthetic problem. In addition, both conservative and surgical treatments have proved to be able to achieve excellent results.

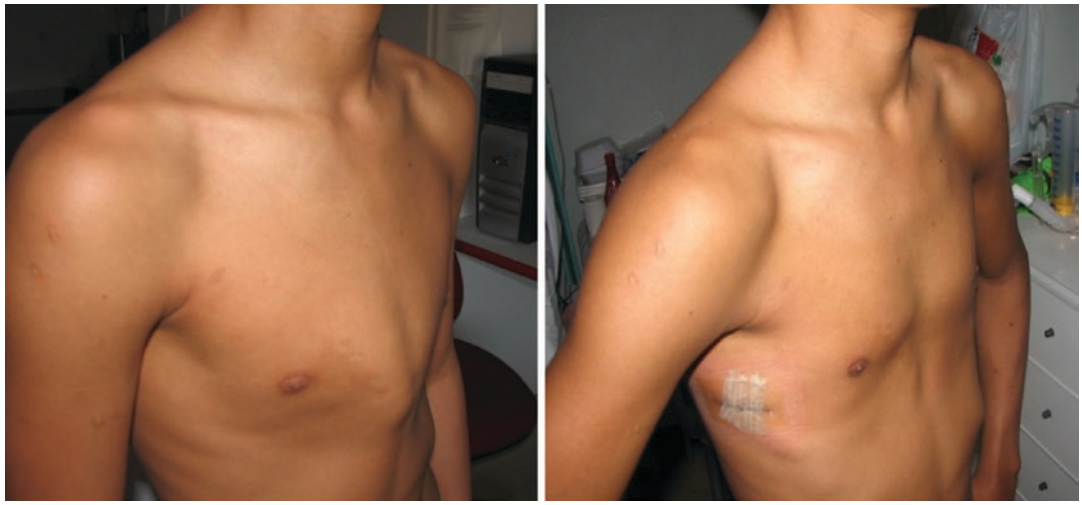

Fig. 9.8 Results after treatment of a patient with PC with Abramson's technique

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Poland Syndrome

10

Michele Torre, Federico Palo, and Maria Victoria Romanini

10.1 Introduction

Poland syndrome (PS) was described for the first time in 1841 by a medicine student, Sir Alfred Poland, who reported, during an autopsy, the case of pectoralis major and minor muscle agenesis associated with other muscle deficiencies and ipsilateral hand brachysyndactyly [1]. The incidence of PS is estimated between 1/30,000 and 1/32,000, [2, 3]. The etiology remains unclear, although a vascular injury of the subclavian artery has been hypothesized [4]. Although familial cases have been described, also by our group [5, 6], the transmission mechanisms are still unknown, and no genetic cause has been identified yet. Usually, PS presents in an isolated form; however, there are typical associations with other syndromes or sequences, i.e., Moebius, Klippel-Feil, and Pierre-Robin syndromes. Therefore, although in most cases PS appears to be sporadic, it seems that the possibility of occurrence of PS in an affected family is higher than that of the general population. For the apparently sporadic cases, which constitute the majority of patients, an autosomal recessive model of transmission can be hypothesized. Alternatively, sporadic cases can be explained by the appearance of de novo mutations. Recent hypotheses seem to support the presence of different genes whose mutations may account for clinical differences among subgroups of patients and for the different inheritance patterns observed, together with environmental factors [7].

10.2 Classification

PS phenotype is extremely variable (Fig. 10.1), so a classification system is required to describe properly every patient.

We have recently proposed [8] a PS classification based on the presence or absence of the two anomalies frequently associated with the defect of pectoral muscles, namely, upper limb and rib cage. We classified PS into three types, according to the absence of these anomalies, the presence of only one, or both of them:

Type-1 or minimal form: isolated pectoral muscle defect (without rib and upper limb anomalies); Type-2 or partial form: pectoral muscle defect associated with rib or upper limb anomalies (Type-2a or upper limb variant: upper limb anomalies without rib anomalies; Type-2b or thoracic variant: rib anomalies without upper limb

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

M. V. Romanini
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_10

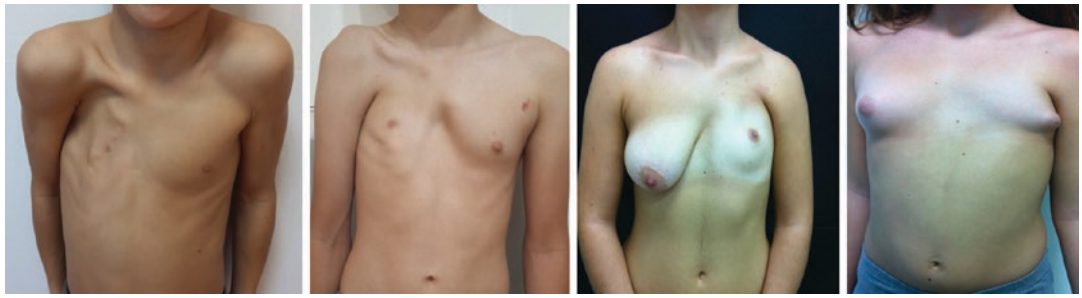

Fig. 10.1 PS phenotype variability

anomalies); Type-3 or complete form: pectoral muscle defect associated with both upper limb and rib anomalies.

In a previous report, we presented the different frequency and phenotypical features of the three PS types [8].

Regarding the thoracic defect, in 2016, our group proposed a new classification of the thoracic features in PS with the aim of taking into account separately all them and classifying the defect according to the severity, similar to the TNM classification used for tumors [9]. The classification published by Romanini et al. [9] is based on the following three thoracic parameters:

- T—thoracic: from T1 (pectoralis muscle defect only) to T4 (muscular, sternal, and rib defect)
- B—breast (for females only): B1 (breast hypoplasia) or B2 (breast aplasia)
- N—nipple–areola complex: from N1 (hypoplasia with dislocation of <2 cm) to N3 (absence of NAC).

10.3 Diagnosis

We present a diagnostic flow chart used in our Institution to investigate the patients with suspect of PS (Fig. 10.2). The confirmation of the diagnosis is usually possible with clinical evaluation. Ultrasound is useful to better define the defect, in particular studying the pectoralis muscle (defining if the defect involves all or partially the three components of the muscle, ie clavicular, sternocostal, and abdominal head), breast, and rib defects. In the case of the suspect of rib agenesis, chest radiographs are useful. In patients with left PS with rib agenesis, dextrocardia has to be investigated with the chest. More invasive radiological investigations such as CT scan are reserved for those cases with severe deformity of the rib cage and for those who have to undergo thoracoplasty. In these patients, CT scan with 3D reconstruction is required to plan the surgical approach.

To rule out other malformations, rarely associated with PS (probably not different from the general population), we suggest performing abdominal ultrasound and echocardiography.

10.4 Treatment

A multidisciplinary approach is strongly recommended. The different types of a thoracic defect will require different treatment according to TBN classification [10] (Fig. 10.3). It is important to start with the treatment planning already during the growth period. A surgical treatment performed during adolescence has been demonstrated to ensure PS patients a better quality of life than a later treatment, both in females and in males [11]. This is due to the strong influence of PS on the cosmetical appearance of young adolescents, the thorax being a very important area of the body for social purposes. The development of this specific surgical algorithm will have to take into account the type of thoracic anomaly, functional and/or aesthetic indication, age, development, and psychological evaluation. This

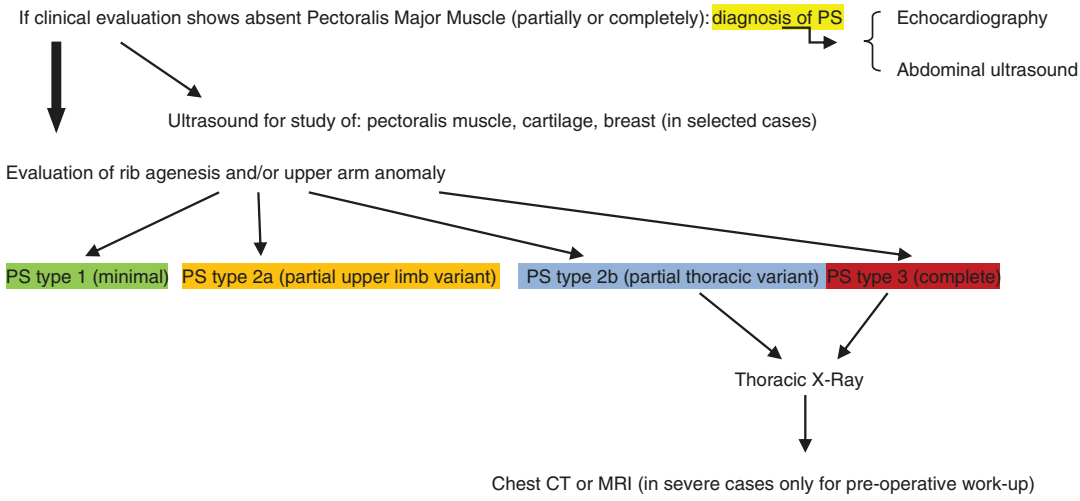

Fig. 10.2 Diagnostic flow chart for PS patients

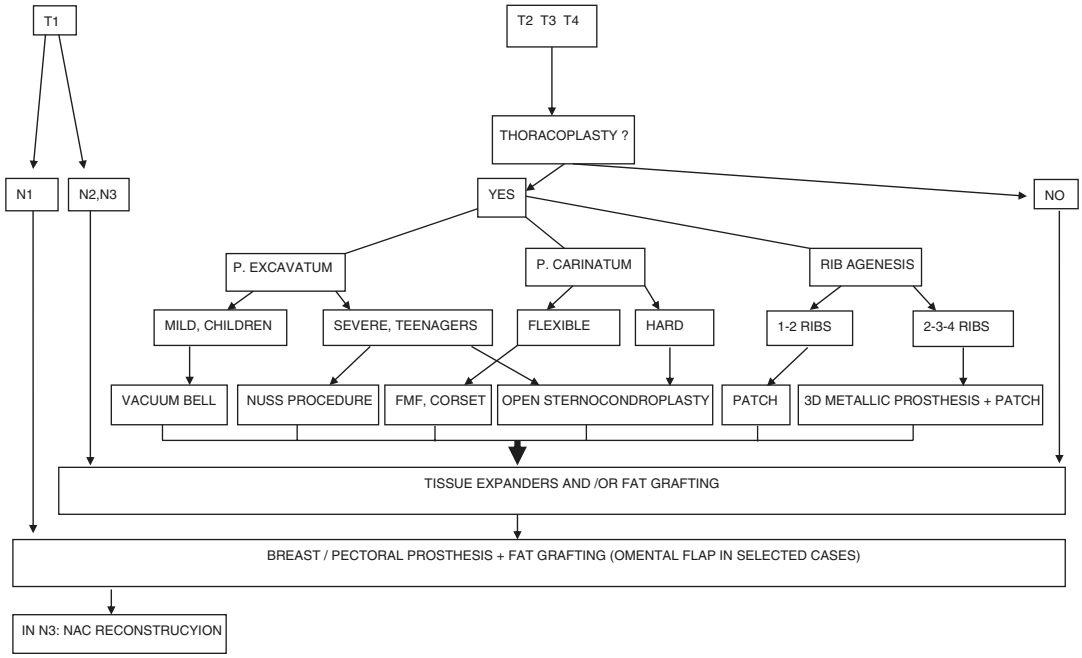

Fig. 10.3 Algorithm of treatment for PS

concept is very different from the classical "better to wait until the end of puberty" that is still adopted in many centers. Increasing our experience during the last 20 years, and thanks to the multidisciplinary approach (in particular, the cooperation between pediatric and plastic surgeons), we have shifted our treatment protocol from a big and invasive operation performed at the end of puberty toward a multistep surgical approach with less invasive techniques starting during adolescence. In our experience, the results are comparable or better, and the patients are much happier to be on the treatment path already during adolescence.

The indication of the treatment of the thoracic defect in PS can be for cosmetical or functional

reasons. The first group covers the large majority of cases.

The functional indications include the problems caused by rib agenesis (paradoxical respiration and lack of protection to the thoracic organs) and by sternal anomalies (in particular, pectus excavatum, causing heart and/or lung compression if severe). Usually, patients with PS and rib cage defect do not have any respiratory impairment, but the lung is often bulging visibly through the defect during forced expiration.

Another theoretical indication of the surgical repair of rib agenesis is the lack of protection on thoracic viscera. Historically, in our institute, all patients with rib agenesis were proposed early thoracoplasty (at the age of few years of life), considering the risk of severe visceral trauma when they were starting to walk. The thoracoplasty was performed with rib transfer or by the implant of absorbable prostheses. In our experience, the transferred ribs tended to be absorbed during the time, so we have abandoned this approach. Regarding synthetic meshes or prostheses to cover the rib defect, nonabsorbable ones are not indicated for pediatric cases, when the rib cage is not fully grown. Unfortunately, the protection given by absorbable prostheses (Lactosorb plates) is only temporary, losing the effect after some months. For this reason, we have now completely abandoned early surgery in PS patients, unless they require rib cage stabilization for respiratory troubles (really uncommon). Moreover, in many cases, the scars of an early surgery resulted, at puberty, cosmetically unacceptable. Finally, to our knowledge, no reports of traumatism on thoracic viscera have never been reported in PS population, so the indication of protection of the thoracic viscera in children is probably not scientifically justified.

Regarding the associated PE or PC (or a mixed PE/PC anomaly), the indications to the surgical treatment for these anomalies do not differ substantially from those for the patients with sternal anomalies without PS. We have performed the Nuss procedure in PS as a first step in case of severe PE associated. The bar was maintained for 3 years as in the other PE. During the last years, there is a trend toward a less and less invasive approach including nonsurgical methods, such as vacuum bell for PE [12] and dynamic compression system for PC [13]. These conservative approaches are in our opinion attractive also in PS patients, particularly during the pediatric period. In PS patients with sternal rotation and contralateral PC, a dynamic compression can derotate the sternum and correct the PC. A vacuum bell can be used to lift the depression of the rib cage on the same side of the pectoralis defect. However, the indication of these treatments is limited to patients with malleable thoraces, and the experience is still too recent to demonstrate any conclusion. Our hope is that conservative treatments could reduce the necessity of surgical open procedures in PS patients or make the operations easier.

In PS patients with associated Currarino-Silverman anomaly of the sternum, an open approach is performed through a small transverse presternal incision two or three anomalous cartilages on each side are removed, and sometimes wedge sternal osteotomy is required to abolish the sternal edge at the level of manubrium. If the lower part of the sternum is compressing the heart, a Nuss bar can be helpful, but in case of mild xiphoid depression, we use to just fill this area with particles of the cartilages removed. The result is usually more than acceptable (Fig. 10.4).

When approaching the patient with PS, depending on TBN classification, the Tanner stage, and the psychological evaluation of the patient, the plastic reconstruction can be the first step, usually with the implant of a tissue expander. Tissue expanders are used to correct the lack of skin and subcutaneous tissue at the axillary level and their nipple–areola dislocation (N2 and N3). In T1N1 patient, this step can be omitted, and the reconstruction is performed usually by the implant of a prosthesis. The expansion of the subcutaneous tissue must proceed very slowly to avoid skin complications. This step usually takes at least 6 months. During this period, fat grafting is recommended whenever possible to enhance the subcutaneous tissue. The last step is the replacement of the expander with a breast (for females) or pectoral (for males) implant. Fat grafting can be repeated if necessary (Fig. 10.3).

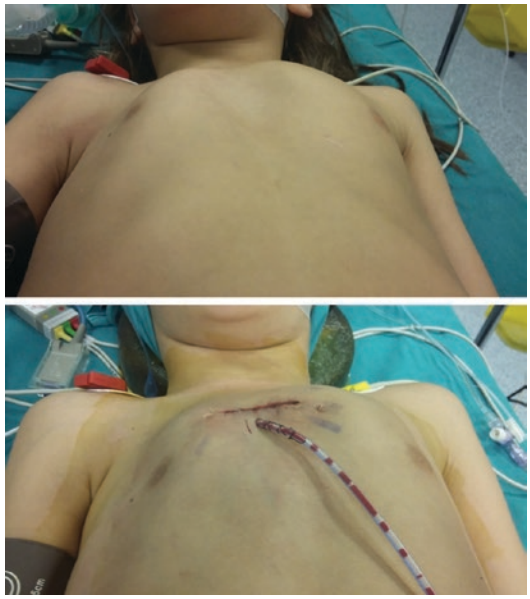

Fig. 10.4 PS and Currarino Silverman anomaly: surgical treatment

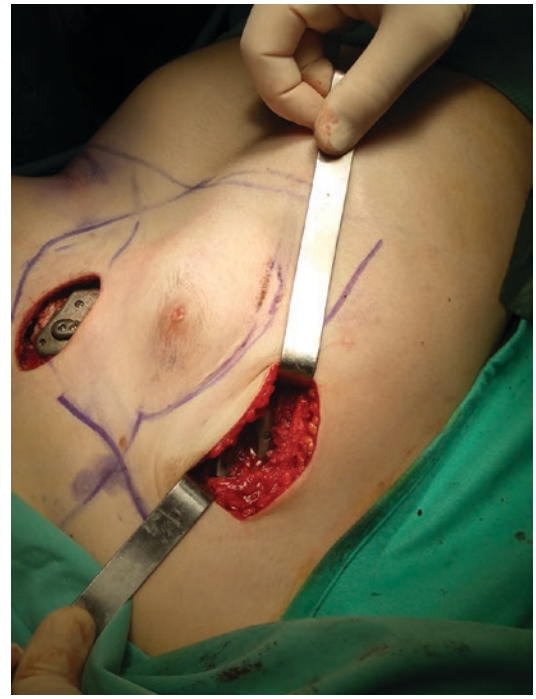

Fig. 10.5 PS T4 correction with a thoracoplasty performed by a team of pediatric surgeons and plastic surgeons

In case of the absence of fat tissue, the omental flap can be considered to cover the prosthesis and give a more natural appearance to the axillary fold in patients with total absence of major pectoralis muscle [14]. As the above-described steps require time to be completed, we again would like to recommend starting with the first steps during adolescence and not, as historically believed, at the end of it in order to allow a proper body image stabilization, thus improving the quality of life [11].

In T4 patients, it is necessary to correct the anterior chest wall contour, to give stability and protection to the rib cage, and to improve cosmetical aspects. We usually start to plan these operations at the beginning of pubertal growth, after throughout multidisciplinary evaluation of the patient, including psychological concerns. We try to address all the above-mentioned indications during the same surgical approach, performed in cooperation with a plastic surgeon.

Usually, anterior chest wall anomalies are corrected through a midline short incision, giving access to the sternum and parasternal cartilages. A tailored approach is required. In most cases, some of the cartilages on the opposite side of the PS defect should be removed, as they are causing asymmetric PC. Less frequently, the same maneuver is required on the same side of the PS defect. Severe sternal rotation or other deformities may require sternal osteotomies.

To correct the rib defect, a second incision, carried out on the axillary line of the same side of PS, is required (Fig. 10.5). The reconstructive approach will vary, mainly according to the numbers of ribs affected: If only one rib is absent, no surgical repair is usually necessary. In the case of two ribs, a Goretex mesh usually is fixing the defect with enough stability. If the agenetic ribs are more than two, we use metallic bars as substitute ribs bridging the lateral rib stumps to the sternum. For this purpose, we have been using for many years pliable titanium bars, cut and shaped accordingly to the patient morphology of the chest defect. These bars are secured to the ribs and the sternum by titanium screws. Above the metallic bars, a Goretex mesh is placed to avoid direct contact between the titanium and the skin

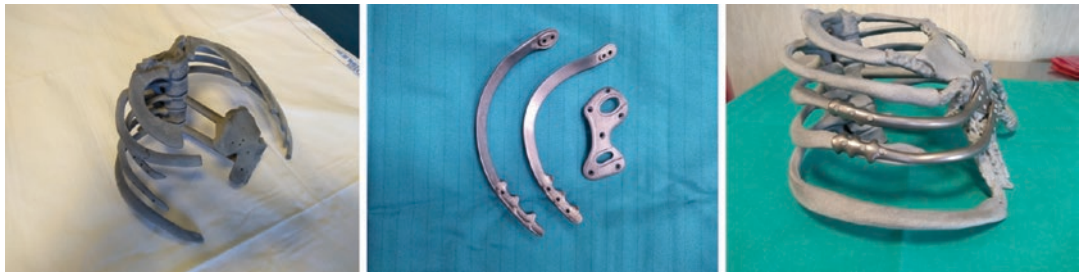

Fig. 10.6 3D custom made metallic prosthesis for thoracoplasty in PS

(or between titanium and other implants), considering that in this area subcutaneous tissue is usually poorly represented. A tissue expander or pectoral/breast prosthesis can be placed above the Goretex sheet. During the last few years, we have been using custom-made titanium prosthesis, built on rib cage models obtained with 3D printing, based on CT scan or MRI of the chest (Fig. 10.6). The software is able to calculate how to build the prosthesis in order to optimize the correction of the affected side of the thorax, at the same time giving the maximum of symmetry with the contralateral side. These new prostheses are inserted through the above-described two incisions (pre-sternal midline, and axillary) and have the advantage of fitting exactly the rib cage defect, improving the final outcome (Fig. 10.5). The prosthesis can be customized preoperatively according to the surgeon's preferences. The shape, size, and orientation of the prosthesis, as well as the caliber and length of the screws, are chosen by the surgeon based on the preoperative imaging, which was impossible when using traditional metallic bars. The prosthesis is then covered by a Gore-Tex sheet, and a tissue expander or breast/pectoral implant can be used above it. In our very initial experience, we have found this new approach advantageous in terms of making reconstructive surgery easier and with better results. The only disadvantage of the 3D customized prostheses is its higher cost. We usually perform a combined surgical approach together with plastic surgeons, so during the same surgery, we repair not only the rib cage defect and the anterior chest wall deformity, but we also start to treat the soft-tissue defect (muscular, nipple, and breast defect). The soft-tissue defect usually requires a multistep approach. Briefly, our plastic surgeons have abandoned the use of the latissimus dorsi flap, as they found it more advantageous to adopt less invasive step-by-step procedures, such as lipofilling, tissue expanders, and pectoral or breast prostheses. In fact, latissimus dorsi is not always available in PS but anyway is an important muscle of the back which our plastic surgeons prefer not to sacrifice, avoiding to leave a significant impact on the back and shoulders in young patients. Conversely, lipofilling is much a less invasive technique that can be repeated and allows to fill cosmetical defects easily. Lipofilling is particularly necessary to be adopted in PS patients, as they have in the affected area a reduction or complete absence of subcutaneous tissue. Nowadays, in our experience, we prefer to associate lipofilling with tissue expanders and breast or pectoral prostheses.

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Jeune Syndrome

11

Michele Torre and Federico Palo

11.1 Introduction and Classification

Jeune syndrome can be congenital or acquired. The latter is an acquired condition after too much aggressive cartilage resections in children, with the loss of the growth center of cartilage ribs leading to rib cage ossification and severe reduction of lung volumes. In the present chapter, we will treat only the congenital form. Congenital Jeune syndrome, also known as asphyxiating thoracic dystrophy (ADT), is a familial autosomal recessive disorder, presenting two variants of diverse severity. The frequency of Jeune syndrome is estimated at around 1/100,000 and 1/130,000 live births. ADT was originally described by Jeune in 1954 [1]. A locus was mapped in chromosome 15q13 [2]. The main feature of ADT is the presence of short, horizontal, and club-ended ribs (Fig. 11.1) with a consequent reduction in both the thoracic diameters and the thoracic volumes, with consequent insufficient lung ventilation (Fig. 11.2). In the severe variant (also known as fatal), respiratory insufficiency occurs during the first years of life. The other variant, a progressive disease developing during adolescence and adult life, is not of pediatric interest so it will not be treated in the present chapter.

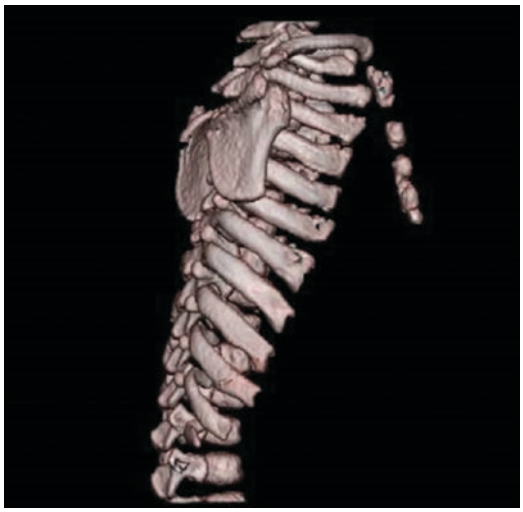

Fig. 11.1 The typical aspect of the ribs in Jeune syndrome. CT scan with 3D reconstruction

11.2 Diagnosis

Patients with ADT present with dwarfism, as they have short limbs but also present anomalies in other organs, with renal, hepatic, and pancreatic disorders. Laryngomalacia or tracheobroncomalacia can be associated.

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_11

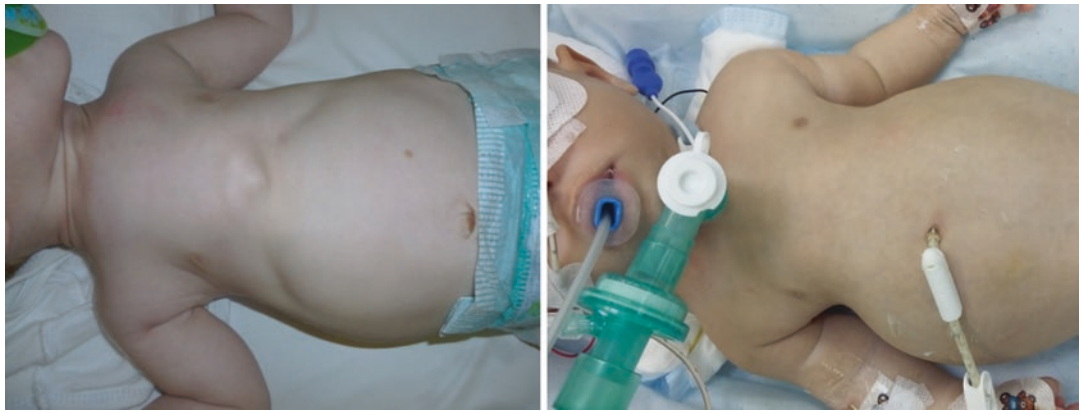

Fig. 11.2 Two patients with Jeune syndrome: the typical aspect of the thorax in the severe variant

Clinical evaluation is usually sufficient to allow diagnosis, which will be confirmed by thoracic radiographs, in particular, useful in the lateral views, better showing the typical ribs. CT scan with 3D reconstruction is also mandatory, as it will depict the morphology of the chest wall in view of a surgical correction (Fig. 11.1). Echocardiography and cardiological evaluation must be focused on evaluating pulmonary hypertension and cor pulmonale, which can occur as a consequence of respiratory insufficiency and can be a relative contraindication to the surgical procedure. Every effort should be made to prevent the occurrence of cor pulmonale.

11.3 Treatment

In severely affected infants, our approach includes a tracheostomy (Fig. 11.2) and mechanical ventilation, which can help maintain the child alive and with better ventilation parameters waiting for the surgery.

The indication of the surgery and its timing in ADT is determined by the following clinical parameters: repeated respiratory infections, respiratory distress, failure to thrive, and pulmonary hypertension. The goal is to perform surgery before cor pulmonale occurs, as this is a point of no return and the possibilities of success are very low. On the other hand, the correction is easier if the patient is grown up, with more developed and solid ribs, so if he is relatively stable, it could be better to wait some months or in less severe cases a few years.

Different approaches have been proposed for ADT: sternal split [3, 4] vertical expandable titanium rib [5], and lateral thoracic expansion (LTE) [6]. At Gaslini Institute, LTE is the preferred surgical approach and will be described in this chapter. We do not have any experience with sternal split and vertical expandable titanium rib.

LTE was described by Davis in 1995 [6]: the lateral chest wall is exposed, the fourth and ninth ribs are split in the middle point, the fifth–sixth rib and the seventh–eighth rib are cut in a staggered fashion (alternatively posterior-anterior-posterior-anterior), and the stumps of the two adjacent ribs are approximated in the midline, so the result obtained will be two longer ribs out of four original short ribs. The expansion effect is based on two factors: (1) creating longer ribs as the stumps of two adjacent ribs are lined up and (2) repositioning the ribs in an oblique direction, instead of the horizontal direction of the ADT ribs. Titanium bars will fix and put together the new rib obtained from the two rib stumps. The bars have to be tight to the ribs, and this can be not easy in small infants due to the fragility of the ribs. Special flanges at the bar ends are designed for this purpose. Usually, we fix the bar to the ribs by using metallic screws. It is important to free the anterior surface of the ribs from muscular and soft tissues so that the bar will stably adhere to the ribs. If the patient is a small infant, it will

be not easy to secure the bar to the ribs, and the results of the literature are worse in these patients. However, in our experience, when indicated by the clinical condition, it is possible to operate on infants, we were able to perform LTE in infants of 2 months.

In Davis' original description of LTE [6], both intercostal muscles and parietal pleura are divided in a staggered fashion in the opposite direction to the rib divisions. Davis described LTE as a monolateral procedure; the second step on the other side was performed usually at least 6 months apart. Other authors have described a bilateral approach in a single step [7]. In the postoperative period after LTE, the patient must be well-ventilated to allow an adequate growth of the lung. If the patient has a tracheostomy, mechanical ventilation through a tracheostomy is helpful.

At the Gaslini Institute, we have performed 12 LTE in 6 patients (Fig. 11.3). In the last two patients, we adopted the bilateral approach as a single step. In our opinion, bilateral approach can be advantageous, allowing the expansion of both sides at the same time, thus theoretically increasing the postoperative benefits of the LTE on ventilation. It is mandatory a strict cooperation with anesthesiologist during the procedure, as the patient will undergo a significantly longer procedure, and the surgeon has to be ready to limit the procedure to one side only in case of anesthesiologic reasons. In our limited experience, we have observed that a longer intraoperative time was well tolerated by our patients. In the postoperative period, one must be prepared for difficulties in managing ventilation, circulation, pain, and possible infections. A well-trained intensive care team together with the surgeons is required to follow-up these patients, and in case of doubt, it is better to perform a staged monoliteral approach We have modified the Davis technique also in another aspect, trying to make the approach less invasive: In some case, we have maintained a more superficial plane just below the posterior wall of the ribs, avoiding opening the pleura and without leaving a thoracic drain in the postoperative period. This approach could be theoretically less effective in expanding the lungs, as the intact pleura could prevent a complete LTE, but, in our opinion, LTE efficacy is mainly due to the reconfiguration of the ribs more than on the space obtained by opening the pleura. With a proper postoperative program of ventilation, we think that the pleura will follow the expansion given to the rib cage by LTE. Data on long-term outcomes and comparison between the original Davis approach and our less invasive technique are not available. All series are small, so it is very difficult to comment on the outcome of LTE for ATD. In Davis's experience, most of the patients improved their respiratory function in short and middle term [8], but we have no results on a long-term basis.

The procedure is performed in only a few centers in the world [8, 9]. In our experience, we have five of six children who survived, the oldest

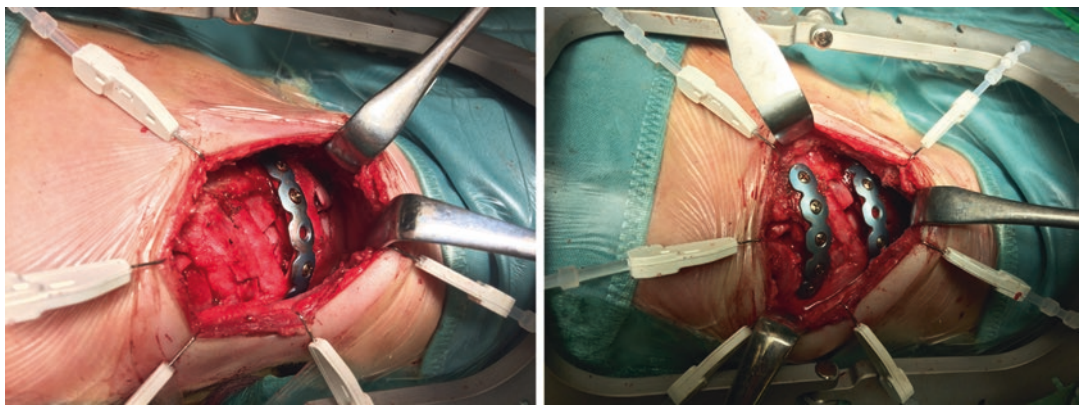

Fig. 11.3 Lateral thoracic expansion with a modified Davies approach

one being 11 years old. All of them have tracheostomy. The patient who died was discharged in stable conditions after few weeks from LTE to the hospital from which he had been referred and died from an acute infective complication.

Our oldest patient is the only one who required an additional procedure to increase the chest wall stability with two more bars (one on each side), the others have not been operated on after LTE, but we suspect that they may require revision surgery at an older age.

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Part IV

Airways

Anomalies of the Larynx

12

Michele Torre, Federico Palo,
and Vittorio Guerriero

12.1 Introduction

Laryngeal anomalies can be encountered by pediatric surgeons as a cause of respiratory distress, especially in infants. Even if many of these anomalies are among the field of competence of otolaryngologists, pediatric surgeons must be aware of the different conditions that can affect the pediatric larynx, often in association with other surgical pathologies. Laryngeal anomalies may represent a real challenge, and they are a paradigm of condition in which a team approach is rewarding. During the last years, in some Centers, as in Gaslini Institute, airway teams have been created to manage these complex patients, including among the others pediatric and cardiac surgeons, otolaryngologists, pulmonologists, anesthesiologist, neonatologists, intensivists, radiologists, gastroenterologists, etc. [1]. Also, in centers without a structured airway team, pediatric surgeons can be called at the bed of these patients just to perform an endoscopic airway evaluation or a tracheostomy, or they are involved as the patients have multiple malformations, including some surgical interest. There are pediatric surgeons who have developed a particular interest in this field, and they can manage these conditions deeply, often in cooperation with the specialists of the airway team. In our opinion, every pediatric surgeon must know the main laryngeal anomalies, be ready at recognizing them, and offer to the patients the proper treatment or derive them a more specialized center. A common surgical procedure such as a tracheostomy must be correctly performed, and only the knowledge of the underlying condition and where and how to perform a tracheostomy is crucial for the chance of success of the subsequent treatments.

In this chapter, we will treat briefly the more common laryngeal anomalies from a pediatric surgeon's perspective. Some of the laryngeal anomalies will be treated in the tracheal anomalies chapter to avoid repetitions.

12.2 Classification

We can distinguish congenital and acquired laryngeal anomalies. The incidence of the congenital anomalies is around 1 in 10,000 to 1 in 50,000 live births [2]. The most common of these is laryngomalacia, accounting for more than 60%

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

V. Guerriero
Pediatric Surgery, PediatricAirwayTeam, IRCCS Giannina Gaslini Genoa, Genoa, Italy
e-mail: vittorioguerriero@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_12

of them. The other two more common congenital conditions are congenital stenosis and vocal cord palsy. Among the uncommon anomalies, we mention webs or atresia, hemangiomas, laryngoceles, and laryngeal clefts.

Among the acquired lesions, the post-intubation stenosis is by far the most common.

An important issue related to laryngeal stenosis (congenital or acquired) is the classification of severity. Classically, the stenoses are classified in four degrees of severity, based on the percentage of the lumen involved by the stenosis:

Grade 1: 0–50%; Grade 2: 50–75%; Grade 3: 75–99%; Grade 4: 100% (no lumen).

Monnier modified the Myer Cotton classification by adding a letter to each degree, according to the presence of comorbidities (b); glottic involvement (c); both comorbidities and glottis involvement (d). For example, stenosis of 80% involving the vocal cord and the subglottic region in a normal baby will be grade 3c; complete stenosis starting from above the vocal cord up to the first tracheal ring in a Down's syndrome and cardiopathic patient will be classified as grade 4d.

12.3 Clinical Presentation, Diagnosis, and Treatment

Clinically, many of the laryngeal anomalies will present similarly: inspiratory stridor, retractions, croup, repeated respiratory infections, or acute and severe onset of respiratory distress, sometimes associated with transient respiratory conditions.

The key to the correct diagnosis is represented by the endoscopy. The other investigations, in particular radiological, may be sometimes useful to complement the endoscopic findings, but they cannot substitute the endoscopy. In our experience, many patients with respiratory symptoms undergo unnecessary or inconclusive CT scan or MRI. It is important to underline that in most cases endoscopic evaluation will be the only tool that will prompt the physician to distinguish among very different conditions with similar clinical aspects. Endoscopy should be performed by experts, as the patient has to be properly sedated and assisted, and this can be very challenging in a patient with an unknown respiratory condition. Basically, two types of airway endoscopy are available and are both useful: flexible and rigid. Through flexible endoscopy, we can evaluate easily and without a big risk of airway trauma the vocal cord mobility, the dynamics of the airway during spontaneous quiet breathing, and forced inspiration and expiration. Rigid endoscopy will show us in a more detailed way the anatomic features of the airway with a big magnification. Both evaluations are useful and ideally should be performed.

- Laryngomalacia:

  It is the most frequent cause of stridor in an infant. Many infants are labeled with the diagnosis of "laryngomalacia" (LM) just because of their inspiratory stridor, but this is incorrect, as other less frequent conditions could give the same symptoms. The diagnosis of LM is not possible without flexible endoscopy, which shows the typical supraglottic obstruction of the larynx from arytenoids, epiglottis, or both. Usually, LM is due to very short aryepiglottic folds (LM type 1). This causes an inward prolapse of arytenoids during inspiration. Less frequently, the obstruction is due to an omega-shaped epiglottis (LM type 2) or a posterior movement of the epiglottic toward the laryngeal lumen (LM type 3). Sometimes there is a combination of more types of LM.

  There is a natural tendency of LM to improve with the age, so in many cases, infants with stridor without other matters of concern (growth retardation, apneas, cyanosis, feeding problems) can be treated conservatively with simple observation, waiting for a spontaneous improvement. In more severe cases, endoscopic supra-glottoplasty is the treatment of choice that can be performed with CO_2 laser or with cold instruments and is able to resolve virtually all cases of LM. Supra-glottoplasty consists in cutting the aryepiglottic folds (in LM type 1) or reshaping the lateral margins epiglottis (in LM type 2) or fixing the epiglottis anteriorly to the tongue (in LM type 3). In

our Institute, ENT surgeons correct LM usually with CO_2 laser, with the patient in spontaneous breathing, at the end of the procedure the patient is sent to the ward, without the need of intensive care treatment.

- Vocal cord paralysis.

Vocal cord paralysis (VCP) can be congenital (idiopathic) or acquired, usually after surgical procedures (on the neck, mediastinum, heart, and big vessels) or neurological conditions. VCP can be unilateral or bilateral. The latter usually causes significant inspiratory dyspnea, as vocal cords (VC) are not abducted during inspiration, thus causing the obstruction. In bilateral VCP, the voice is usually not much impaired, while the patients with monoliteral VCP are frequently dysphonic. The diagnosis is based on flexible endoscopy with the patient awake or very lightly sedated. The correct diagnosis of VCP, in particular bilateral, requires experience. If sedation is too deep, impaired movement of VC can be due to the sedation itself. The endoscopist should therefore be sure that the patient is breathing alone and sufficiently awake so that the movement of the VC cannot be influenced by any drugs. Sometimes, bilateral VCP can be missed, as the VC moves symmetrically during the spontaneous breathing in a passive way for an inward negative pressure (like a suction) generated by the inspiration. In patients with the normal movement of VC, they spread during inspiration and move medially during expiration, while in patients with bilateral VCP, we observe the reverse: VCs are approximated toward the midline during inspiration (for the abovementioned suction effect), and they open more during expiration, spread apart by the air flowing out the trachea.

Regarding treatment, most bilateral VCP classically requires a tracheostomy. To avoid tracheostomy, bilateral endoscopic cricoid split and balloon dilatation seems a promising technique for neonates with congenital bilateral VCP. After the procedure, a big endotracheal tube is left as a stent for 10–15 days, then the patient is extubated, and usually does not require a tracheostomy.

Unilateral VCP usually does not require any urgent treatment, as the respiratory distress is absent or very little. The issue is more on the voice quality.

It is well known that VCP, both congenital and acquired, can improve spontaneously, so it is usually accepted as a conservative treatment, waiting for spontaneous improvement. The point is how much time has one to wait for it (in our experience spontaneous recovery can occur even after 6 or more years). To evaluate the recovery of VC movements, classically endoscopic evaluations are repeated every 6–12 months. More recently, ultrasound evaluation has been demonstrated to be useful for detecting VC movement in a less invasive way [3]. Another tool for evaluating VC function is the measurement of the evoked potentials through a little electrode inserted in the laryngeal muscles during an endoscopy. This gives us information about the innervation of the muscles and possibility of recovery.

The treatment of VCP is controversial. Many endoscopic techniques have been described, trying to improve the glottis space and improve airflow. Among them, posterior cordotomy [4], VC lateralization [5], and arytenoid latero-abduction [6] are the most popular. Another option is represented by a posterior cartilage graft that can be performed either endoscopically [7] or through an open approach (Figs. 12.1 and 12.2).

- Congenital laryngeal stenosis (Fig. 12.3):

Congenital subglottic stenosis is defined as a subglottic diameter of less than 4 mm in a neonate and less than 3 mm in a preterm baby. Congenital stenosis is much less frequent than acquired stenosis. The cricoid cartilage is abnormal in size or shape. The most frequent types of congenital subglottic stenosis are elliptic cricoid; thick anterior lamina of cricoid ring; and generalized thickening of cricoid ring. Clinical presentation is usually biphasic stridor or recurrent episodes of croup. Some cases are asymptomatic as the stenosis is not critical (grade 1) and become clinically evident during an episode of airway infection. The diagnosis is made during endoscopy

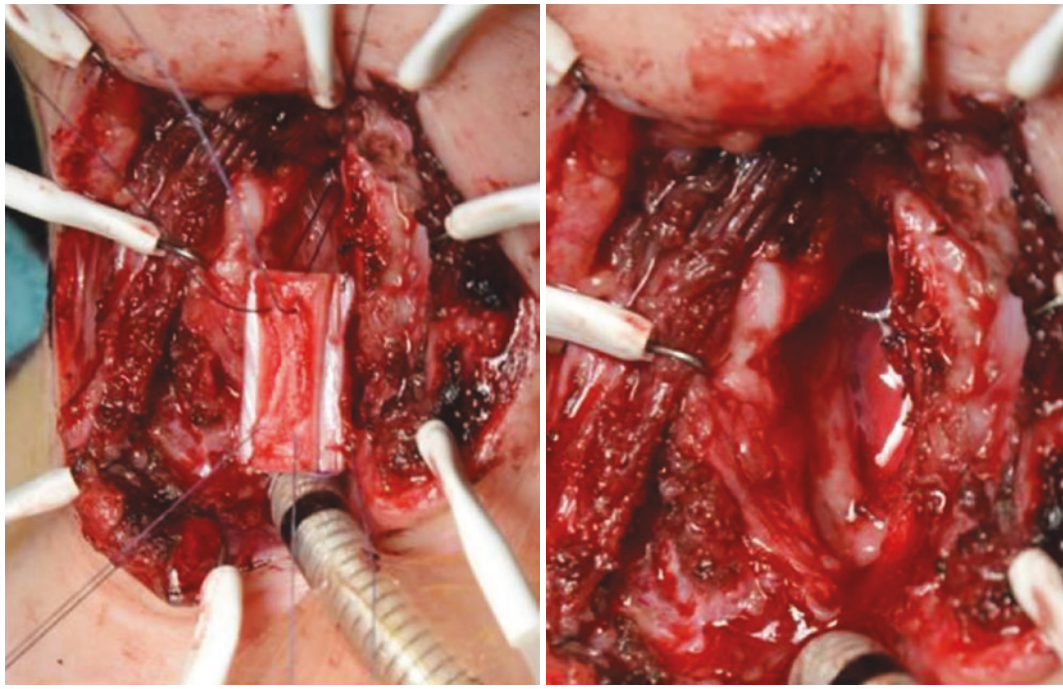

Fig. 12.1 Posterior cartilage graft for treatment of a congenital vocal cord paralysis: the graft before (left) and after (right) suture to the posterior cricoids plate

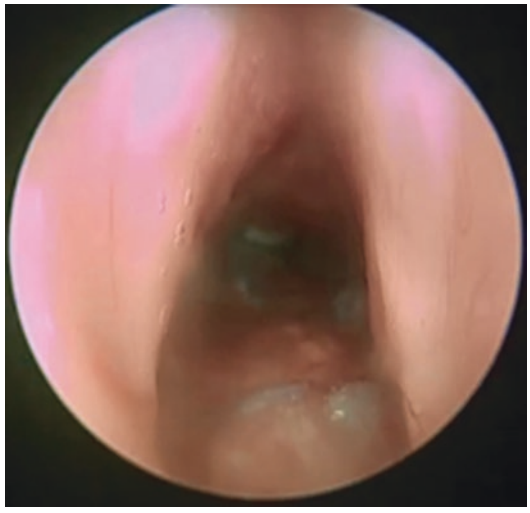

Fig. 12.2 Endoscopic view of a posterior graft

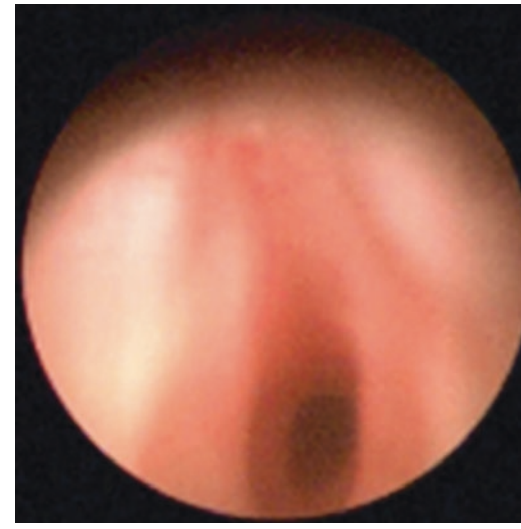

Fig. 12.3 Congenital laryngeal stenosis

(Fig. 12.4). It is important to calibrate the diameter of the stenosis with a tube in order to classify it into one the four degrees. Congenital subglottic stenosis does not respond to endoscopic treatment, as the cartilage is anomalous, and this cannot be modified endoscopically. Open laryngotracheal reconstruction with an anterior and posterior cartilage graft or partial crico-tracheal resection are the treatments of choice for symptomatic stenosis.

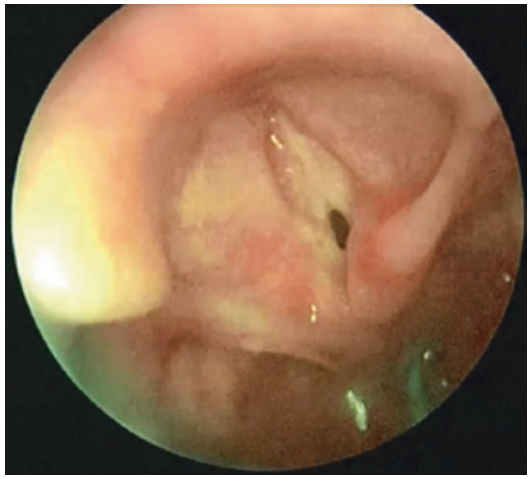

Fig. 12.4 Laryngeal web type 4

- Acquired laryngotracheal stenosis: see the chapter on tracheal malformations.
- Laryngeal clefts: see the chapter on tracheal malformations.
- Laryngeal webs and atresia:

  Laryngeal webs (LW) are due to defects of recanalization of the primitive larynx. Laryngeal atresia is the extreme form of web and is incompatible with life. LW are classified according to their severity in 4°:

  Type 1 is a thin anterior web occluding less than 35% of the glottis, and there is no subglottic involvement; type 2 is a slightly thicker web occluding 35–50% of the glottis and extending sometimes minimally in subglottic region; type 3 is a thick web occluding 50–75% of the glottis and always extending in subglottic region; and type 4 occludes 75–90% of the glottis with significant cartilaginous subglottic stenosis (Fig. 5).

  The symptoms are related to voice quality (from mild hoarseness in grade 1 to aphonia in grade 4) and in more severe grades respiratory distress is present.

  The treatment can be performed endoscopically to improve the quality of the voice in grades 1 and 2. In grade 3, an open approach is sometimes required if the subglottic component of the malformation is significant. In case of prevalent glottic web without subglottic significant stenosis, endoscopic approach can be preferred. In type 4 an open approach is always required with the aim of resolving not only the glottic web but also the subglottic stenosis (Fig. 12.4). In many of LW grade 4, a tracheotomy is required before the repair.

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Anomalies of the Trachea

13

Michele Torre and Marcello Carlucci

13.1 Tracheal Agenesis

Tracheal agenesis is characterized by the absence of the cervical trachea and the direct connection of the bronchus or carina with the esophagus. It is a very rare congenital anomaly occurring in 1:50.000 to 1:100.000 live births and generally is a lethal condition; it presents usually male prevalence and associated anomalies are present in 90% of cases, especially involving the larynx; prematurity is frequently associated (50%) [2].

13.1.1 Classification

In 1962, Floyd proposed an anatomical classification of tracheal agenesis [3]:

- Type 1 (20% of cases)—Agenesis of the upper trachea with normal but short distal trachea, normal bronchus, and tracheoesophageal fistula.
- Type 2 (60% of cases)—Complete tracheal agenesis with normal carina and bronchus and presence of a fistula between esophagus and carina.
- Type 3 (20% of cases)—Complete tracheal agenesis with bronchus arising directly from the esophagus separately.

13.1.2 Diagnosis

The diagnosis is usually made at birth: the neonate presents severe respiratory distress, is unable to cry, and cannot be intubated but shows an improvement when ventilated by a facemask. Attempts at intubation are unsuccessful, but accidental esophageal intubation may improve the respiratory pattern if a tracheoesophageal fistula is present. Prenatal ultrasound can show bilateral hyperechoic lungs and ascites if the trachea or larynx is obstructed completely. The presence of lung secretions causes overdistension of the lungs, and compression on the heart can lead to cardiac failure. If a tracheoesophageal fistula is present this pattern is less severe and detectable on ultrasound as the fluids escape into the gastrointestinal system.

13.1.3 Treatment

An EXIT procedure or ECMO must be performed expeditiously upon delivery. The presence of an esophageal fistula is lifesaving because it allows

M. Torre (✉)
Unit of Pediatric Thoracic and Airway Surgery, IRCCS Istituto Giannina Gaslin, Genova, Italy
e-mail: micheletorre@gaslini.org

M. Carlucci
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, Genoa, Italy
e-mail: marcellocarlucci@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_13

esophageal intubation and mechanical ventilation. Due to the rarity, variability, and complexity of this malformation, there is no well-established and systematic surgical approach. Surgery aims to recreate a steady trachea by using the esophagus and re-establish digestive continuity with a colon interposition [4, 5].

13.1.4 Conclusion

Tracheal agenesis is a very rare condition associated with a high rate of mortality. Antenatal diagnosis could be suspected, but usually, the diagnosis is clinical and made at birth. The presence of a fistula between the esophagus and the lower airways is lifesaving and permits the esophageal ventilation of the lungs. Suddenly EXIT or ECMO procedures can be associated with patient survival; surgery aims to replace the trachea using the esophagus and restore the esophageal continuity by bowel interposition. Advances in tracheal allotransplantation and tissue bioengineering could provide better management and outcomes in the future.

13.2 Laryngotracheoesophageal Cleft

It is defined as an abnormal communication between the airway and the esophagus; its extension could be variable: a posterior laryngeal cleft (LC) may be limited to the inter-arytenoid region or involve the cricoid lamina; if the cleft extends into the cervical or thoracic trachea, or even to the bronchus, it is named a laryngotracheoesophageal cleft (LTOC) [6]. Pathogenesis of LC and LTOC is related to failure in the formation of the tracheoesophageal septum. LC and LTOC represent very rare conditions occurring in 0.5–1.5% of all congenital laryngeal anomalies; a mild male predominance is described. There is a high prevalence of associated anomalies, especially tracheobronchomalacia, gastroesophageal reflux, and tracheoesophageal fistula (almost in 30% of cases) with or without esophageal atresia. Other malformations involving the gastrointestinal and genitourinary tracts, cardiovascular system, or cervicofacial region may be associated with syndromic or non-syndromic patterns. The most frequent syndromes associated with these congenital anomalies are:

- G (Opitz-Frias) syndrome—It includes other defects of the median line: cleft lip, cleft palate, and hypospadias, with abnormal implantation of the external ears and hypertelorism.
- The Pallister–Hall syndrome—It includes central nervous system anomalies (hypothalamic hamartoma and hypopituitarism); imperforate anus, cardiac, pulmonary, and renal malformations; and distal extremity anomalies (syndactyly and postaxial polydactyly).
- VACTERL association—Vertebral, Anorectal, Cardiac, Tracheoesophageal, Renal, and Limb anomalies.
- CHARGE association—Coloboma, Heart disease, choanal Atresia, growth and mental Retardation, and Genital and Ear anomalies.

13.2.1 Classification

In 1989, Benjamin and Inglis proposed an anatomical classification based on the extension of the defect [7]:

- Type I—Supraglottic interarytenoid cleft extending down to the level of the vocal cords.
- Type II—Partial cricoid cleft extending beyond the level of the vocal cords.
- Type III—LTOC extending down into the cervical, extrathoracic trachea.
- Type IV—LTOC extending into the thoracic trachea and occasionally into one main-stem bronchus.

This classification was modified by the author with the advent of endoscopic repair of extrathoracic clefts; he describes a Type 0 cleft (submucosal cleft) and divided Type III and IV in Type III a (complete cleft of the cricoid plate), Type IIIb (LTOC extending into the extra-thoracic

portion of the trachea), Type IVa (LTOC extending to the carina), and Type IVb (LTOC extending into one main-stem bronchus).

13.2.2 Diagnosis

The diagnosis is suspected on the clinical presentation. The severity of symptoms is strictly related to the extent of the defect. Association of feeding and respiratory difficulties should alert the physician even if these are not pathognomonic of LTOC. Characteristically, cough or early choking during feeding is secondary to aspiration. Patients may present with airway and/or impairments. Laryngomalacia and tracheomalacia are frequently associated; these, along with discoordinate pharyngolaryngeal function, severe gastroesophageal reflux disease, and central neurological disorders, are the most frequent differential diagnosis presenting at this stage. Type I clefts are almost asymptomatic, except for some aspiration during feeding. Sometimes stridor, a hoarse cry, and episodes of choking and coughing during feeding could be associated. Type II and III clefts present with the same symptoms but more frequent and severe. Aspiration and recurrent pneumonia always present. Type IV clefts usually present with early respiratory distress, coughing, choking, and apnoeic and cyanotic spells. Once the LTOC is suspected on the clinical history, chest X-rays can reveal signs of aspiration pneumonia, and a contrast swallow study can show the spill-over into the upper airway. However, these findings are not pathognomonic of LTOC. The gold standard for the diagnosis is endoscopy (Fig. 13.1); trans-nasal flexible laryngoscopy, during spontaneous respiration, assesses vocal cord function, laryngo and tracheomalacia, and extrinsic tracheal compressions. Rigid laryngotracheobronchoscopy under general anesthesia represents the best examination for the diagnosis of LTOC. To complete the patient's assessment, considering the high percentage of associated anomalies, a systematic evaluation must be done, including genetic consultation, cardiac and renal ultrasounds, spine radiographs, and thoracoabdominal CT scan if required.

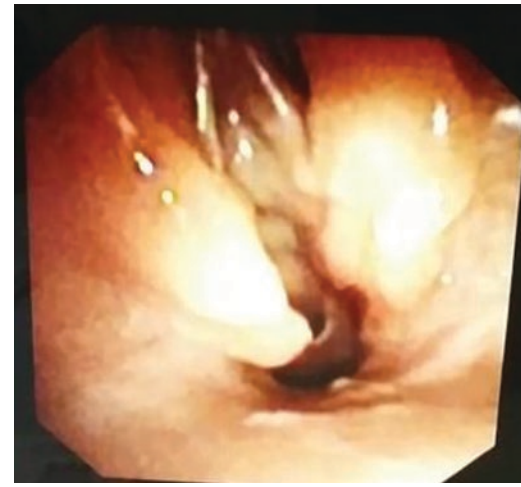

Fig. 13.1 Endoscopic aspect of an LTOC

13.2.3 Treatment

Type I laryngeal cleft generally does not need to be repaired. The majority of patients with type I are asymptomatic. If there is no clinical and radiological pulmonary aspiration, surgical intervention is not required. Type II–III and IV require surgical repair. Type IV repair is extremely complex and associated with severe tracheomalacia, requiring in many cases ventilation support, tracheostomy, and even gastrostomy. Endoscopic repair is indicated in symptomatic Type I clefts and in all Type II; with advancements in anesthesiologic and endoscopic techniques, even some Type IIIa and IIIb could be operated with an endoscopic approach if severe comorbidities are ruled out. Type III and Type IV are usually approached by an open transtracheal through the neck and even combine approach with a midsternotomy [2, 5, 8–10]. All types of clefts could be repaired by this approach. Prior to surgery, it is important to stabilize the airways to prevent pneumonia and to reduce aspirations. For Type I, II, and IIIa clefts, the herniation of pharyngeal mucosa could represent a protective mechanism against the aspirations; intubation is not suggested in these cases because of the risk of inflammation of the laryngotracheal mucosa and consequent wound breakdown after repair. Noninvasive ventilation represents the best

choice for these patients. In Type IIIb clefts associated with severe tracheomalacia, it is preferable to perform a tracheostomy below the distal end of the cleft, while in Type IV clefts deep intubation into the tracheoesophageal slit is usually sufficient to provide respiratory support until the operation. Rates of a second surgery for failed primary repair range from 11% to 50% for shorter clefts. The mortality rate is about 14% for shorter clefts and 50% for Type IV clefts [5, 10].

13.2.3.1 Endoscopic Repair

If possible, endoscopic repair should be performed avoiding tracheotomy or with a low tracheotomy, if required, to facilitate the procedure. The operation is performed under general anesthesia in spontaneous respiration. A rigid laryngoscope is placed distally to the vocal cord to spread apart the LTOC and gain access to its caudal extremity. CO_2 laser is used to incise the mucosa of the lateral edges of the cleft from the distal end to the level of the cuneiform cartilages. The tracheal mucosa is then separated from the pharyngoesophageal mucosal layer. Cleft is sutured in two layers: first, the closure is performed in the distal to proximal direction by placing inverted stitches through the mucosa of the posterior membranous trachea; the second layer of sutures is placed similarly in the distal to proximal direction on the mucosal surface of the pharyngoesophageal repair [2, 5, 10]. The most common and feared complication is a residual fistula resulting from the partial breakdown of the suture line [5].

13.2.3.2 Surgical Open Repair (Fig. 13.2)

Usually, a low tracheostomy and gastrostomy are established at the beginning of the surgery. For extra thoracic clefts, an extended laryngotracheal fissure is carried out over the entire length of the cleft just above the tracheostomy, dividing the

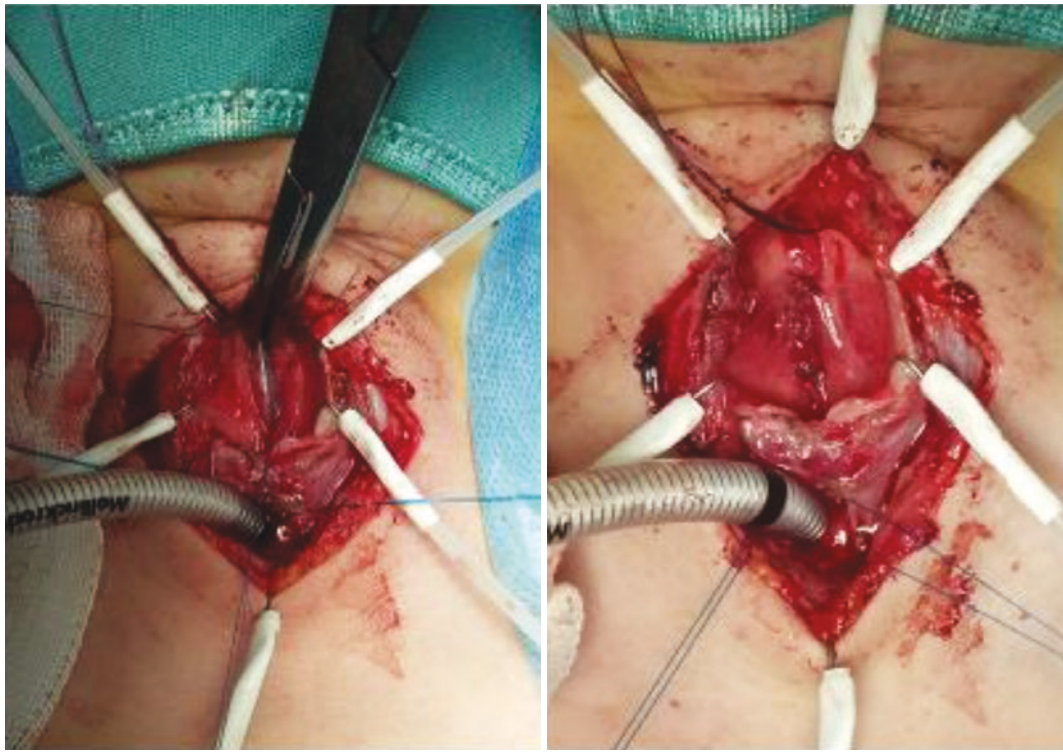

Fig. 13.2 Open surgical repair of an LTOC: trachea is opened anteriorly, and the cleft is visible (note the nasogastric tube) (left); the posterior wall is sutured in double-layer (right)

anterior laryngeal commissure exactly in the midline. Then, the mucosa is incised slightly off-side of the mucosal ridge, on one side more in the pharyngeal, and on the other side more in the tracheal aspect of the mucosa. The anterior esophageal wall is the first layer that has been closed by interrupted sutures up to the level of the posterior laryngeal commissure. A costal cartilage graft is placed as for conventional laryngotracheal reconstruction in order to restore an adequate interarytenoid space, and perichondrium or periosteum graft or synthetic fibrin is interposed between the tracheal and the esophageal layers [5, 10]. Then, the tracheal mucosa is sutured. In the case of large Type IV cleft, support by ECMO is recommended [2, 10]. In these cases, an anterior cervicothoracic approach is preferred; the tracheoesophageal common cavity is opened longitudinally along the right postero-lateral angle of the trachea. The tracheal posterior wall is then reconstructed by using a flap of the oesophageal wall. The remaining esophagus is sutured longitudinally on itself, and a flap of muscular tissue (usually the sternohyoid muscle) is interposed between the trachea and the esophagus to prevent the risk of fistula formation. This repair is carried out up to the inferior border of the cricoid ring. At the level of the larynx, a transverse section between the cricoid and the first tracheal ring is performed, along with a full laryngofissure, providing an optimal exposure for reconstructing the laryngeal and upper tracheal components of the cleft. Surgical repair of the laryngeal cleft is performed with the same technique used for extra-thoracic LTCO repair.

13.2.4 Conclusions

LTOCs represent rare congenital conditions the severity of which can vary from isolated laryngeal cleft to more severe defects affecting the trachea and bronchus. Anatomically, LTOC is classified into four types depending on defect extension. This condition is frequently associated with laryngomalacia and/or tracheomalacia and with other congenital anomalies in syndromic or non-syndromic patterns (30%). The diagnosis is based on the suspicion index. Sometimes, the symptoms are nonspecific, but most have associated respiratory symptoms. Characteristically, cough or early choking during feeding is secondary to aspiration. The definitive diagnosis must be performed using an endoscopic evaluation with rigid scope under general anesthesia. Extra thoracic clefts could be operated by an endoscopic approach and usually do not require tracheostomy; severe clefts are extremely complex and associated with severe tracheomalacia, requiring in many cases ventilation support, tracheostomy, and even gastrostomy. In the case of larger cleft, support with ECMO during repair is recommended. A two-layer repair is essential, dissecting the tracheal and esophageal mucosal layer and performing a closing of both mucosa separately. The mortality rate is about 14% for shorter clefts and 50% for Type IV clefts.

13.3 Tracheomalacia

Tracheomalacia (TM) is defined as an abnormal softness of the tracheal wall due to structural anomalies of the tracheal cartilaginous and/or posterior membrane, determining more than 50% collapsibility of the tracheal lumen during expiration. When it extends to the bronchi, it is called tracheobronchomalacia or brochomalacia if it is limited to the bronchus. Airway malacia, including laryngomalacia, tracheomalacia, and bronchomalacia, represents 50% of all congenital anomalies of the pediatric airway, and it is characterized by an excessive dynamic collapse during the respiratory cycle due to the increased airway compliance. The incidence of TM is estimated to be 1:2500 newborns [11, 12]. The embryological development of the trachea from the foregut provides insights into the pathogenesis of congenital tracheomalacia. The common embryologic origin of the trachea and esophagus explains the frequent association between TM and esophageal atresia with tracheoesophageal fistula. At the end of the embryogenesis, trachea and esophagus are fully separated; the normal trachea is composed of C-shaped cartilage rings anteriorly and of a muscular part (pars membranacea) posteriorly that could be considered as the

residual of the floppy component of the primitive foregut. The ratio among the cartilage and floppy part of the normal trachea is about 4.5/1 [2]. TM is due to a more developed pars membranacea and a weakness of the cartilaginous rings resulting, during expirations (especially the forced ones, i.e. cough), in intrathoracic tracheal collapse, with lumen reduction more than the physiological rate of 30–35%. The anterior collapse of the trachea is caused by the weakness of the tracheal rings, while the posterior collapse is due to the protrusion of the pars membranacea into the tracheal lumen. The prevalence of anterior or posterior protrusion is important to choose the correct treatment to be performed.

13.3.1 Classification

TM is classified into primary and secondary forms [11].

- Primary diffuse TM—It is a rare congenital condition occurring frequently in preterm, characterized by a weak and abnormally shaped long segment of the tracheal framework due to immaturity of the tracheal rings. This condition usually improves spontaneously during the first 2 years of life.
- Secondary TM—It is characterized by a localized weakness of the trachea associated with other mediastinal anomalies or tracheal conditions.
  - TM associated with esophageal anomalies (oesophageal atresia, LTOC): This is the most represented group, and TM is typically localized at the posterior wall, more affected than the anterior one.
  - TM associated extrinsic compressions: This is a heterogeneous group of patients in who the trachea is compressed by incomplete rings (aberrant innominate artery, aberrant right subclavian artery, and anomalous left pulmonary artery sling), complete rings (double aortic arch and right aortic arch), cardiac conditions (enlarged left atrium or pulmonary arteries), and mediastinal masses (bronchogenic or thymic cysts, lymphatic malformations, teratoma, neuroblastoma, and lymphoma).
  - TM associated with tracheostomy or other tracheal conditions: This can be a localized TM, mainly due to the tracheostomy cannula or previous intubation, or diffuse, associated with laryngomalacia or bronchomalacia.

In order to facilitate describing the individual patient variation, discussion among clinicians and treatment planning a classification based on the site of TM was developed; valuation with dynamic bronchoscopy permits to divide the trachea into three segments [11]:

- T1 from the cricoid to the thoracic inlet (most frequently compressed by thyroid goiters or congenital neck cysts or masses);
- T2 from the thoracic inlet to the innominate artery (can be compressed by the innominate artery on its left anterior surface);
- T3 from the innominate artery to the top of the carina (compression is often associated with the aorta anterolaterally).

The carina is evaluated independently; the left mainstem bronchus is divided into three sections: L1 to L3 from proximal to distal, with L2 defined as the segment where the bronchus crosses over the descending aorta. The right mainstem bronchus is divided roughly in half length-wise, proximal to distal, and designated as R1 and R2. L1 compression is associated with the main pulmonary artery, L2 can be compressed anteriorly by the left pulmonary artery and posteriorly by the descending aorta, L3 compression is typically anterior and associated with the left pulmonary artery, and R1 and R2 are compressed anteriorly by the right pulmonary artery.

13.3.2 Diagnosis

TM is suspected based on clinical history. It is associated with a large spectrum of respiratory symptoms depending on the length of the malacic tract; symptoms usually appear when the tracheal

lumen is reduced by more than 50%, causing respiratory obstruction and reduction in clearance of secretions. Main symptoms are barky cough, recurrent respiratory tract infections, BRUEs (brief, resolved, unexplained events, previous known as ALTEs, apparent life-threatening events), with forced exhalation, laughing and coughing, exercise intolerance, extubation failure, prolonged infections, lung atelectasis, and bronchiectasis.

The gold standard for the diagnosis is the endoscopic evaluation during spontaneous breathing and must give information about the percentage of lumen occlusion, the site of TM (proximal, media, distal), its extensions into the main bronchus, and the prevalence of anterior or posterior collapse. Brochography could be useful to demonstrate TM. CT scans are indicated to evaluate vascular anomalies or associated mediastinal anomalies [2, 5].

13.3.3 Treatment

TM could be treated by a conservative approach (medical therapy, ventilator support, and respiratory rehabilitation maneuvers) or surgically. There is still no consensus on the ideal treatment of TM, and indications to conservative or surgical management are not universally established [13]. TM could present a spontaneous resolution in the first 2 years of age when it presents in its mild forms; conservative management could be indicated in these patients. Nevertheless, the ideal treatment must be evaluated on the clinical history of each case. The primary indications for surgical intervention include cyanotic and/or apnoeic episodes, recurrent pneumonia (>3 episodes per year), and the inability to extubate the patient owing to CPAP requirement. Developing bronchiectasis and exercise intolerance are emerging surgical indications. A single BRUE event with evidence of TBM is also an indication for hospitalization until urgent surgical repair can take place [11]. Several treatments are described, depending on the severity, localization, and pathogenesis of the TM [5].

13.3.3.1 Aortopexy

Aortopexy represents the most common surgical operation in the treatment of TM because of its good results (more than 80% of treated cases) [13] and relatively low technical difficulty. By suspending the anterior aorta to the posterior sternal wall, a suspension of the anterior tracheal wall is obtained, due to the presence of ligamentous tissue between the anterior trachea and posterior aorta (Fig. 13.3). Basic concepts are not to dissect the aorta posteriorly and create enough space between the aorta and the posterior sternal surface, performing partial or total thymectomy. The surgical operation is performed through a left anterior thoracotomy or mini-sternotomy, even if the thoracoscopic approach has been described. It is suggested to perform an intraoperative endoscopy to check the improvement of the airway caliber. Postoperative complications could be hemothorax or pneumothorax (3%), atelectasis (2.5%), cardiac spillover (2%), and phrenic nerve injury (1.3%) [13].

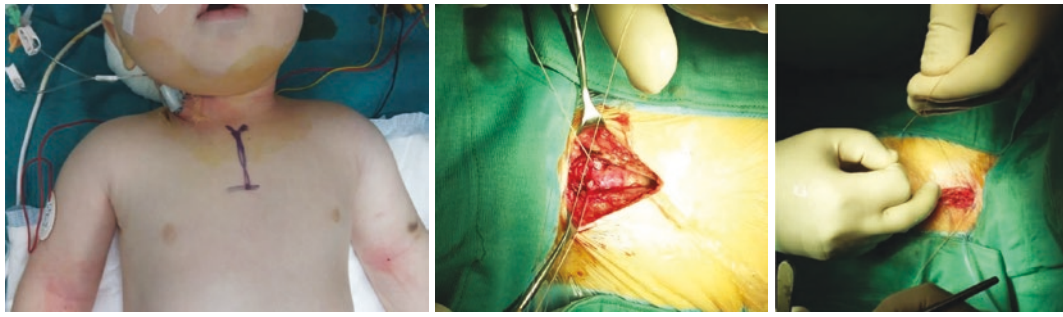

Fig. 13.3 Anterior aortopexy. Surgical approach (left), the stitches are passed through the tracheal wall (center) and knotted above the sternum (right)

13.3.3.2 Tracheopexy

Tracheopexy is defined as the suspension of the anterior and/or posterior tracheal wall in order to obtain enlargement of the airway lumen. It could be performed at every tracheal level, even at the bronchus.

- Anterior tracheopexy T1: It is indicated in the case of tracheal and or bronchial anterior collapse. Different techniques were proposed based on the tracheal segment involved.
  - Cervical anterior tracheopexy—Indicated in the short cervical tract of TM. A dissection of a sternal manubrium patch is performed, and a nonabsorbable suture is passed at this point through the medium part of the collapsed trachea and then ancorated to the cricoid cartilage (Azizkhan technique) [14].
  - Median trachea anterior tracheopexy T2—Indicated in TM at the median trachea. By cervicotomy, it is extended to the sternal manubrium, the thymic isthmus is divided, and tracheopexy is achieved suspending the anterior tracheal wall and the innominate artery at the posterior sternal wall (Vaishanav and MacKinnon technique) [15]. A modification of this technique considers the resection of the right thymic lobe, extending the dissection up to the carena (Morabito technique) [16].
  - Distal trachea anterior tracheopexyT3—Indicated in case of severe intrathoracic TM. Through a partial sternotomy, the thymus is removed and a trans pericardic dissection of the trachea and main bronchus is performed. Both aorta and innominate arteries are suspended at the posterior sternal wall with pledgets as the anterior tracheal wall, by the interposition of the bovine pericardium to avoid injuries of the great vessels (Jennings technique) [17, 18].
- Posterior tracheopexy (Fig. 13.4): This technique permits the treatment of TM affecting multiple segments (mainly T2 and T3, but even cervical trachea could be treated by posterior tracheopexy) and bronchomalacia at the same time. It consists of the suspension of the posterior tracheal wall at the anterior longitudinal spinal ligament. The surgical approach could be by median sternotomy, thoracotomy, and lateral neck dissection; recently, thoracoscopic and robotic approaches were described. The intraoperative endoscopic check aimed to exclude full-thickness sutures passing through the tracheal wall and to assess the lumen improvement, it is mandatory. Once the identification of the anterior longitudinal spinal ligament is exposed, dissecting the thoracic duct laterally to the aortic arch, posterior tracheopexy is accomplished by passing autologous pledget polypropylene sutures into but not through the posterior tracheal membrane, taking care to stay extraluminal, and securing them to the ligament [17–21].

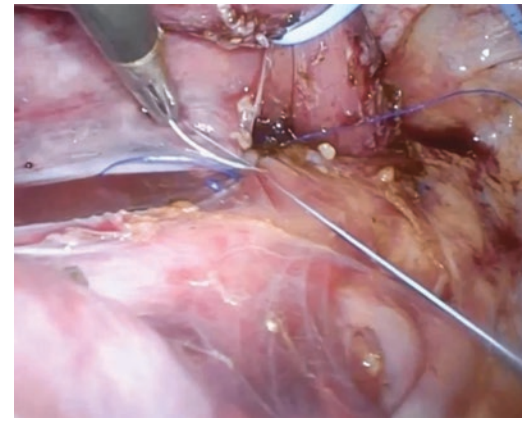

Fig. 13.4 Posterior tracheopexy. The pars membranacea of the trachea is sutured to the anterior spinal ligament. The esophagus is lifted up

13.3.3.3 Internal Stent

Internal stenting in pediatric patients is still debated, as an ideal stent is not still available. Internal stenting is associated with high rates of complications and morbidity, thus limiting indications to selected cases, when open or endoscopic procedures are not feasible.

- Metallic stent—Usually, vascular stents adapted to the airway; even if it permits a significant enlargement of the lumen, it needs to be substi-

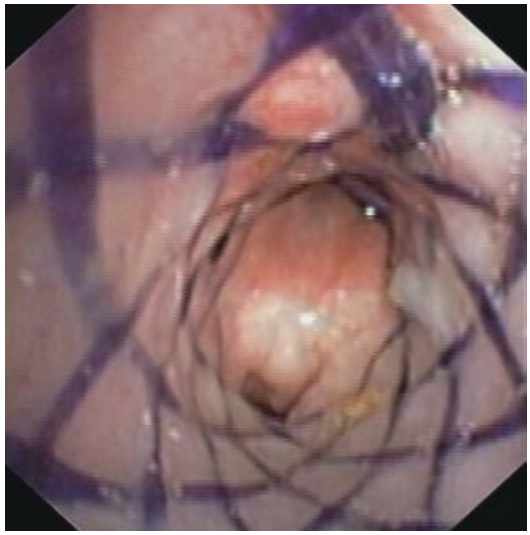

Fig. 13.5 Absorbable PDS stent for tracheomalacia

tuted or dilated at distance; these maneuvers could be associated with major complications such as hemorrhages and airway lesions. The development of granulation is also associated with the presence of these stents [22, 23].

- Silicon stent—These stents are associated with lower complications during their removal, but they migrate more frequently and do not permit mucociliary clearance. Granulomas formation is associated.
- Biodegradable stent—These stents present the advantage of needing removal; moreover, they permit a good expansion of the lumen and are not associated with migration; the mesh structure permits the mucociliary clearance. On the other side, granulomas are even associated and the dilatation effect is temporary [24] (Fig. 13.5).

13.3.3.4 External Splint

Even this technique requires a surgical approach, and it avoids the complications related to the contact between foreign bodies and airway mucosa. It is indicated for long forms of TM. Synthetic materials, such as Silastic meshes and ceramic rings, have been reported, but concern for foreign body reaction, infection, and erosion have limited their use. Autologous rib and absorbable miniplates have been fixed on either side of the cartilaginous rings to stabilize and enforce long-segment TM (Fig. 13.6). A newer treatment with external, custom 3D printed splints has been reported [25].

13.3.4 Conclusions

Tracheomalacia describes increased collapsibility of the trachea and bronchi that is greatest on forced expiration; it is caused by intrinsic tracheal weakness, some forms of tracheal deformation, and extrinsic compression. TM is the most common congenital tracheal anomaly, affecting 1 in 2500 newborns and is often associated with other congenital anomalies and syndromes. TM is often associated with recurrent and prolonged respiratory tract infections, can lead to chronic lung disease, and can be fatal in its most severe form. Diagnosis is made through history and physical examination, dynamic airway CT scan, and tracheal bronchoscopy. A multidisciplinary approach to these patients is essential, and a well-established classification scheme facilitates discussion of individual patients among professionals and guides appropriate management. There is still poor information on ideal TM treatment; medical management includes nebulizer treatments, minimal use of inhaled corticosteroids, gastroesophageal reflux disease therapy, and continuous positive airway pressure. The primary treatment modalities described include tracheostomy, tracheal stents, and anterioraortopexy. Recently, anterior and posterior tracheopexy and aortopexy, even by thoracoscopic or robotic approach, were described and must be considered in TM treatment. Use of internal stents is limited to selected cases due to the related complications; among stents, absorbable ones represent the best choice. External splinting with autologous or absorbable plates represent a valid treatment for long-segment TM.

13.4 Congenital Tracheal Stenosis

Congenital tracheal stenosis (CTS) (Fig. 13.7) is a true embryological abnormality of the tracheal skeleton characterized by the presence of complete tracheal rings along the stenotic segment,

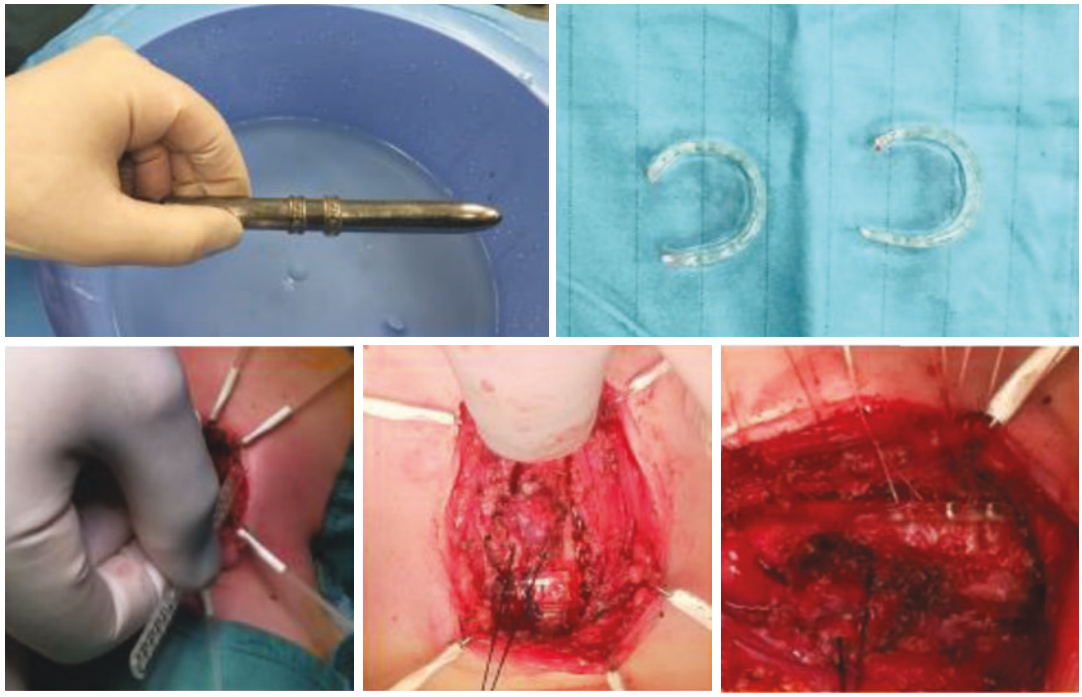

Fig. 13.6 External splint for tracheomalacia. Synthetic absorbable plates can be shaped in hot water, and the tracheal wall is pexied to the plates

resulting in a fixed narrow tracheal lumen. Usually, there is no transition zone between the normal and the complete rings; rarely it is possible to identify a transitional tracheal segment with rings passing from a normal horseshoe shape to a complete "O" one [26].

Short segment stenosis involves less than 50% of tracheal length; long segment stenosis can involve the whole trachea, even extending beyond the carina. The etiology and pathogenesis are unknown, but they are the result of a developmental abnormality.

Intrinsic structural tracheal anomalies are very rare conditions, and, among these, CTS has an estimated incidence of 1 in 64,500 births [1]. Associated anomalies are frequently reported: anomalous left pulmonary artery sling (50% of cases) and tracheal origin of the right upper lobe bronchus (bronchus suis, 50% of cases); other cardiovascular anomalies, such as carina trifurcation, lung agenesis or hypoplasia, anorectal malformations, VACTER association, Down syndrome, and situs viscerum inversus, can be associated [1, 27].

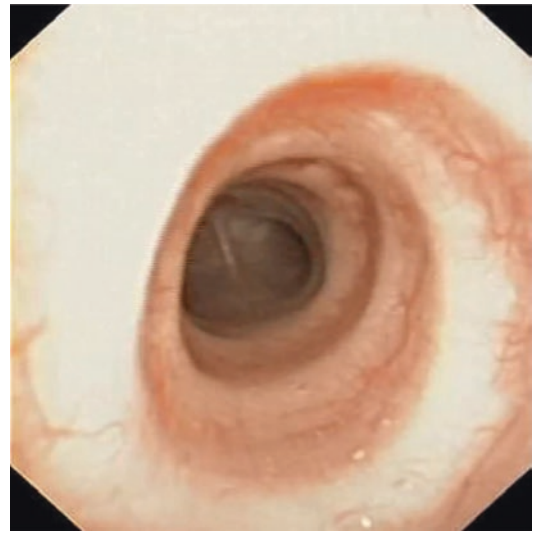

Fig. 13.7 Complete rings in congenital tracheal stenosis

13.4.1 Classification

The anatomical classification was proposed by Grillo and identifies four main types of CTS [28]:

- Type 1: *generalized tracheal hypoplasia*. Almost the entire trachea is stenotic while only the first to fourth cranial rings are normal. It is the most frequent type and usually compromised more than 85% of tracheal length.
- Type 2: *funnel-shaped tracheal narrowing*. The abnormal tracheal segment varies by location and length but always has a funnel configuration that is shaped from the cranial to caudal direction.
- Type 3: *segmental tracheal stenosis*. Short-segment stenosis (Stenosis is less than 50% of the tracheal length) is located at different levels of the trachea, at times below an anomalous right upper lobe bronchus.
- Type 4: *bridge bronchus stenosis.* It could be considered a variant of Type III, characterized by the presence of an abnormal upper right bronchus and a long bridge bronchus. The anomalous right upper lobe bronchus is in the proximity of the carina, and via horizontally branching bronchi, the stenotic bridge bronchus connects the proximal trachea to the rest of the lungs.

Recently, the Great Ormond Street Group proposed a new classification, considering the length of the stenosis and the tracheobronchial anatomy [29]. Airway stenosis is divided into tracheal stenosis (short or long segment if less or more than 50%, respectively) and tracheobronchial stenosis; each group was then subdivided according to the morphology of the tracheobronchial tree into normal anatomy, tracheal bronchus, carina trifurcation, and single lung.

13.4.2 Diagnosis

Symptoms can start at birth with respiratory difficulty, the need of intubation, or, more commonly, during the first months of life, probably due to a disproportion during the activity between the respiratory demands and the possibilities of ventilation through a stenotic airway. Sometimes CTS becomes evident by difficult intubation during general anesthesia. Typically, symptoms are biphasic stridor or noisy breathing with prolonged expiratory phase, chest retractions, cyanotic attacks, and lung infections. Respiratory symptoms in infants are occasionally particularly severe: Attempts of mechanical ventilation can be frustrating, as the obstruction is sometimes extended throughout the entire trachea or involve the bronchi. Tracheostomy in these cases is not useful, and ECMO represents the only way to ensure patient' survival. On the other hand, some patients are not compromised in the everyday life and present symptoms only under exercise (stridor, impossibility to strong activities).

The gold standard for diagnosis of CTS is the endoscopy under general anesthesia, accomplished both by flexible or by rigid bronchoscopy. In neonates and in the case of infected airways, complete tracheal rings recognition could be difficult. CT scan or MRI with digital subtraction is the investigation that can define with accuracy the morphology of the tracheobronchial tree, the length and the degree of the stenosis, and study associated cardiovascular anomalies. Bronchography is less used than past, but it still has an important role in defining the morphology of trachea, carina, and bronchi and the dynamics during respiration; it is useful also to evaluate the growth of the trachea and postoperative results.

13.4.3 Treatment

Indication to surgical treatment depends on the presence of respiratory symptoms. There is controversy regarding the surgical indication in patients with mild symptoms because the growth of the tracheal diameter over the years might reduce symptoms, as supposed by some authors [30]. It has been suggested that the presence of a pulmonary artery sling is an indication for surgery even in patients with mild symptoms.

Single-stage surgery is always preferential, and concomitant cardiovascular anomalies should be repaired at the same time. Balloon dilatation associated with the posterior longitudinal division of the circular cartilaginous rings is discussed because it is considered dangerous and because of the complications related to stenting a small airway [31]. Depending on the type of CTS and comorbidities, different surgical techniques were described.

13.4.3.1 Resection with End-to-End Anastomosis

This approach is indicated in Type 3 CTS involving less than one-third of tracheal length. The operation consists of a horizontal suprasternal cervicotomy. By dividing the midline, the strap muscles, the thyroid isthmus, and the thymus, the trachea is exposed; its dissection should be limited to its anterior and lateral portions, in order to avoid vascular and nervous injuries. Stay sutures are placed distal to the stenotic segment. The caudal transverse section between the tracheal rings is conducted first, keeping the posterior membranous trachea temporarily intact. At this stage, the distal trachea stump can be intubated and ventilated. The tracheal proximal transverse section, including the posterior membranous wall, is made without separation from the esophageal wall, allowing for full preservation of the adjacent blood supply to the trachea. Dissection in the tracheoesophageal plane is only carried out over the stenotic segment down to the distal tracheal stump, and the membranous trachea is sectioned transversally. Anastomosis is performed with inverted sutures and starts from the posterior tracheal membranous wall. Stay sutures are placed under tension to approximate both tracheal stumps; a trans-anastomotic tube is passed, and all anterior and lateral are placed before being tied on the outside. Stenosis located at the distal trachea or associated with concomitant cardiovascular anomalies benefit from sternotomy with cardiopulmonary bypass [5, 32].

13.4.3.2 Anterior Patch Tracheoplasty

This technique could be indicated for patients with long-segment CTS. Through a median sternotomy, the trachea is exposed by retracting the aortic arch and the great vessels. Tracheal stenosis is incised over all its length in the midline. Costal cartilage grafts are harvested from the lower part of the sternotomy, carved into the appropriate shape, and sutured in situ with the perichondrium facing the lumen [33]. A pericardial patch technique was also described [34]. Currently, this technique is not recommended anymore, as it has been replaced by the "slide tracheoplasty" technique [5].

13.4.3.3 Tracheal Autograft

Exposure and opening of the anterior tracheal wall are performed as for the patch tracheoplasty. The narrowest central portion of the stenosis is resected paying attention to not remove more than 30% of the trachea. The excised midportion of the posterior trachea is used as a free tracheal autograft. Tracheal stumps are anastomosed posteriorly, and the free graft is sculptured and sutured in situ on the anterior defect; if necessary, any residual proximal anterior opening is closed with a pericardial patch. This technique has been replaced by the "slide tracheoplasty" technique [5, 30].

13.4.3.4 Slide Tracheoplasty

It is the most performed operation for long CTS and consists of a tracheal transection at the midpoint of stenosis and expansion of both tracheal segments, following a slide, permitting steady cartilaginous support and a fully mucosalized inner lumen [5, 26, 35]. Through a small collar incision, the upper trachea is prepared anteriorly and laterally from the cricoid ring down to the carina, with careful preservation of the posterolateral vascular supply. Lower dissection extended to both mainstem bronchi is performed through a median sternotomy. The cardiac surgeon first corrects cardiac and vascular anomalies, consisting mostly of an anomalous left pulmonary artery sling. Airway reconstruction can then be initiated, while the patient is still on cardiopulmonary bypass. The trachea is fully incised horizontally at its midpoint, and the proximal stump is freed circumferentially until the posterior membranous trachea of the first one or

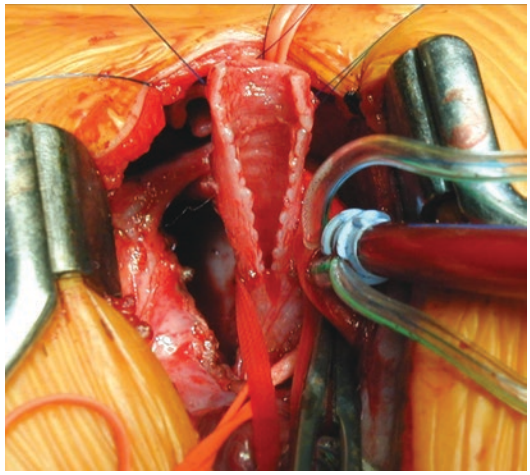

Fig. 13.8 Slide tracheoplasty. The distal stump of the trachea is opened anteriorly

two normal tracheal rings. The distal stump (Fig. 13.8) is split longitudinally on its anterior surface down to the carina. The posterior wall of the proximal segment is divided longitudinally until the last circular ring is divided. The end of both segments is spatulated, and the two stumps are approximated slowly by sliding one over the other and sutured by interrupted sutures (oval-shaped posterior-to-anterior anastomosis).

13.4.3.5 Tracheoplasty with Cadaveric Tracheal Homografts

This technique is not indicated for the treatment of primary long-form CTS but was applied for recurrent tracheal stenosis after failed primary patch tracheoplasties. It is based on the same principles of patch tracheoplasty: The stenotic segment is opened on its anterior wall, and slits in the posterior wall are created in order to enlarge it. A silicone stent is placed and fixed on the tracheal wall; the tracheal homograft is trimmed so as to reflect the defect of the anterior and lateral trachea and sutured in place [5, 36, 37].

13.4.4 Conclusions

CTS is an anatomical anomaly of the trachea, characterized by the presence of complete cartilaginous rings. It is a very rare condition, occurring in 50% of cases in association with anomalous left pulmonary artery sling and/or tracheal origin of the right upper lobe bronchus. Anatomical classification in four types was proposed by Grillo; trachea could be affected for a short or a long tract. Clinical presentation could be different with severe symptoms presenting at birth or mild ones presenting later on in life. Diagnosis is based on endoscopy and CT or MRI studies with 3D reconstruction. Several techniques were proposed but, nowadays, two operations are mostly performed: short forms could be treated by resection and direct anastomosis, while long forms are treated by slide tracheoplasty.

Slide tracheoplasty has become increasingly successful over the past two decades such that long-term survival now exceeds 88%, with normalization of quality of life for patients with non-syndromic-associated CTS. Although slide tracheoplasty can be successfully performed in patients with normal pulmonary anatomy, this procedure in patients with abnormal pulmonary anatomy can be more difficult and may require prolonged mechanical ventilation and the use of ECMO.

13.5 Traumatic Acquired Lesions

Traumatic tracheal lesions could be caused by acute or chronic trauma on the airway. Tracheostomy cannula can cause chronic damage to the tracheal wall; typically, supra-stomal collapse develops as a result of the action of the curved cannula against the anterior wall of the trachea which crushes down. At this level, a granuloma can be the consequence of the collapse. Another less frequent cannula-related lesion is a granuloma caused by the thrusting of the tip of the cannula against the tracheal wall, in case of inadequate placement or length of the cannula. Cuffed cannula can also cause tracheal damage. Tracheal lesions by acute traumas are very rare. Traumas are more frequently blunt than penetrating. The most frequent causes are sport and play activities,

intubation, or endoscopic maneuvers. In blunt traumas, a severe thoracic compression increases significantly intratracheal pressure; if this happens against a closed glottis, tracheal fracture can occur. The most commonly affected area is the posterior pars membranacea, while fractures of cartilaginous rings are extraordinarily rare.

13.5.1 Diagnosis

Patients with supra-stomal collapse are usually asymptomatic, as the cannula bypasses the problem. This condition is very commonly detected during routine endoscopy check.

On the other hand, patients with granuloma at the tip of the cannula are more at risk of developing acute life-threatening respiratory distress. Acute trauma can hesitate in severe respiratory distress; neck emphysema (with subcutaneous crepitus) or tenderness, pneumomediastinum, pneumothorax, dyspnea, and hemoptysis are all possible early signs of a tracheal lesion. Neck or mediastinal infections are late complications of this kind of injury. Endoscopy and/or radiologic evaluation are helpful for diagnosis. Flexible tracheoscopy can be performed even in severe injuries through the endotracheal tube, withdrawing it progressively. CT scan is the best radiological investigation for the study of the acute tracheal traumatic lesion.

13.5.2 Treatment

Supra-stomal collapse can be corrected at the time of tracheostomy closure. Granulomas on the tip of the cannula must be removed once diagnosed, by forceps or laser resection. After acute traumas, surgery must be performed in unstable cases or if cartilage is exposed, which can lead to significant posttraumatic stenosis. If the patient is well and the lesion is in the posterior wall of the trachea, conservative treatment is the best option, as good spontaneous healing usually occurs.

13.5.3 Tracheal Lesions

Tracheal lesions (TL) are rare entities, with an estimated incidence of 1/60.000 live births, and experience managing these anomalies is consequently limited and widely dispersed. TL can be divided into congenital and acquired anomalies. Among the first ones, tracheomalacia (TM) and congenital tracheal stenosis (CTS) are the most common, while laryngotracheoesophageal clefts, tracheal webs, and tracheal agenesis are rare. Other congenital tracheal malformations such as tracheoesophageal fistula are described in other chapters of this book. Even if an embryological model explaining congenital tracheal anomalies remains elusive, it has been noted, as these are frequently associated with other mediastinal anomalies due to the intimate embryological development of the trachea, esophagus, and cardiovascular system. Acquired anomalies are usually represented by stenosis secondary to intubations and trauma or extrinsic compressions from mediastinal masses, as neoplasms or bronchogenic cysts.

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Tracheostomy

14

Roberto D'Agostino and Federico Palo

14.1 Introduction

Tracheotomy (from the Greek "to cut the trachea") is one of the oldest, most known, and performed procedures in the whole general surgery. Its purpose is to create a direct connection between the patient's outside and inside (airways) to overcome several obstacles that prevent air from reaching the lungs naturally.

The first certain document of tracheostomy is attributed to Galeno about some procedure performed by the famous practitioner Asclepiade of Bytinia around the end of II century A.C. in Rome ("Asclepiadem ultimum auxilium potuit in iis qui maxime soffocantur laringem incidere). In the Seventh century, Paul of Egina subdivided tracheostomy into two different methods for the emergency and the routine: He proposed to cut both skin and trachea in the first case (our cricothyrotomy) and, with a more respectful surgery for cutaneous, muscular and vascular layers, to incise, in the other case, the tracheal wall between the second and the third ring (as we perform nowadays in the majority of patients). But the recurrent epidemic of diphtheria in the XVIII century was the moment that particularly contributed to the spread of tracheostomy as a rescue-for-life surgery. Finally, the famous French surgeon Bretonneau (the father of word "diphteria" and the curve cannula inventor) and specially his learner Trousseau set the definitive rules of tracheostomy:

supine and not sitting patient, hyperextended head, incision of the layers till finding the tracheal wall and vertical cut between the second and third ring, need of surgery when respiratory conditions are not extremely compromised ("il faut la pratiquer le plus tot possible").

Nowadays, tracheostomy has great importance as a rescue-for-life procedure and as a necessary surgery in complex pathologies that need prolonged intubation and/or assisted ventilation.

14.2 Indications

Nowadays tracheostomy has three major indications:

1. To get over a severe obstruction of the upper airways
2. To protect and clean lower airways from tough and recurrent secretions
3. To support ventilation in general pathologies with hypo-oxygenation [1–6].

In the first case, we consider:

R. D'Agostino (✉)
Pediatric Airway Team, IRCCS Giannina Gaslini Genoa, Genoa, Italy
e-mail: robertodagostino@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_14

1. Tumors blocking pharynx, larynx, or upper trachea
2. Congenital or acquired anomalies with airways stenosis
3. Fractures or lesions of larynx and/or trachea
4. Bilateral paralysis of vocal cords
5. Severe maxillo-facial traumas with soft tissues edema with subsequent stenosis
6. Nontraumatic edema of soft tissues (infective, allergic, inflammatory)
7. Facial or neck or mucosal wall burns of pharynx and larynx
8. Embedded and nonremovable foreign bodies [1, 2, 5, 6]

In the second case, we consider:

1. deficient cough besides chest or abdominal surgery with the presence of persistent and thick secretions
2. bronchopneumonia with important deficiency of ventilation and secretion drainage
3. vomiting with gastric fluid or feed inhalation (in unconscious patients) [1–3, 5]

In children, we must add these diseases:

1. laryngeal cleft with inhalation
2. persistent and recurrent trachea-bronchial fistula
3. pharyngolaryngeal incoordination for fluids or saliva inhalation [2–5]

In the third case, we consider:

1. Obstructive lung diseases and severe alveolar hypoventilation (emphysema, bronchiectasis, and asthma).
2. Respiratory depression by drug intoxication or by poisoning.
3. Severe thorax traumas with a crush, rib fractures, emphysema, or pneumothorax;
4. Paralysis of severe decrease of lung bellow (muscular or neurological diseases which involve the thorax wall).

   In newborns, we must add the "distress respiratory syndrome" due to congenital or acquired lack to produce so much surfactant to allow alveolar distension [2, 5].

14.3 Procedure

As we saw, tracheostomy is surgery to allow a direct connection between the neck skin and the tracheal wall to enable the air to flow to the lower airways.

In Italian traditional surgery, we distinguish:

Tracheostomy: when we suture the whole tracheal wall to the skin;

Tracheotomy: when we suture only the external tracheal wall to the skin;

Cricotomy: when we cut the cricothyroid membrane in an emergency [6].

On the contrary in the literature and in the most used surgical books, the authors usually distinguish:

Over-isthmic tracheotomy: when the opening of the trachea is performed above the thyroid isthmus (1–2° ring):

Trans-isthmic tracheotomy: when the opening of the trachea is performed through the thyroid isthmus after its cutting (2–3° or rarely 4° ring);

Under-isthmic tracheotomy: when the opening of the trachea is performed under the thyroid isthmus (4–5–6° ring) [1–5].

In children or newborns, the procedure must take into account some important anatomical differences:

- larynx position (usually higher in the neck)
- more open angle of the thyroid cartilage with less protrusion on the neck skin (less evident Adam's apple)
- tracheal rings not often recognizable (due to their immaturity)
- more jutting structures (hyoid bone and cricoid instead of thyroid)
- thyroid gland with a little and usually movable isthmus [4, 5].

In any case, the tracheostomy presents some common elements to which we must add variants considering single-case needs and personal skill:

The first step is the skin incision with horizontal cervical cut usually in the middle point between cricoid and jugular; we dissect subcutaneous tissue layer by layer, we opened pre-thyroid

muscle in the middle, we cut and open cervical bands, we move or cut thyroid isthmus which crosses the trachea at 2° or 3°ring, we point out a stripping tracheal wall removing any tissue adherence, and finally we cut the trachea with a vertical cut on the midline.

At this point several variants exist:

1. position
2. opening shape
3. tracheal wall connection to the skin.

Regarding the position, besides the three variants described, many others exist:

1. Tracheostomy for ventilatory support: 3°or 4° ring
2. Tracheostomy for laryngotracheal stenosis: 1° or 6–7°ring
3. Tracheostomy for tracheal stenosis: exactly through the stenosis
4. Tracheostomy for intra-thoracic stenosis: 6–7° ring with a long stenting tailored cannula
5. Tracheostomy for recurrent stenosis in a previous T.: in the same stenosis position [4–6].

Regarding the shape of the tracheal wall opening, we have many variants available: we must take into account before the child's age and after the perspective of a more or less long stay of tracheostomy.

In children, we prefer a linear incision of the tracheal wall without the sacrifice of tracheal tissue for a complete recovery allowing in case of tracheostomy removing, even if the cannula reintroduction may become less easy.

In adults, we must prefer an easy and safe cannula reintroduction in case of accidental removal even if we must lose a tracheal tissue quote; in such cases, the variants are:

- complete anterior opening (removing a square of the anterior wall)
- superior window (square incision on three sides—inferior, and lateral left and right without complete removing)
- inferior window (square incision on three sides—superior and lateral left and right without complete removing)

In the end, regarding the connection of the tracheal wall to the skin, we distinguish two variants:

- Tracheotomy when we suture only the external tracheal wall to the skin: it is the procedure of second choice when we suppose a short-term tracheostomy.
- Tracheostomy when we suture the whole tracheal wall to the skin to realize a stable connection; it is the first-choice procedure especially when we suppose to maintain the tracheostomy for a long time [6].

A brief note deserves the always more diffuse practice of percutaneous tracheostomy, especially in E.R units; it is a faster procedure, usually performed by the anesthetist himself because it does not need a surgical time of neck opening. It consists of a progressive cracking of superficial layers till the tracheal wall through different devices, which allows also a more and more efficient stoma dilatation, till reaching a sufficient way for the cannula introduction.

But this tracheostomy is a "blind" procedure, it may undergo unpredictable anatomic alterations, and it implies a risk of structural lesions of the trachea especially of the posterior wall with an early or late possible tracheoesophageal fistula. This is the reason why this procedure is limited to adults or teenagers [5].

14.4 Complications

They are divided into early and late complications.

The early complications are:

- bleeding
- subcutaneous emphysema
- infections
- accidental decannulation [1, 3–6]

The late ones are:

- excessive granulation tissue and suprastomal collapse
- stenosis or granulations of the tip of the cannula
- granulations of the stoma which may complicate the cannula introduction
- innominate artery fistula (rare)
- lower respiratory tract infections
- accidental decannulation with obstruction
- wrong-way creation during the introduction [2, 4–6].

14.5 Final Comments

Nowadays, tracheostomy has yet great importance as a rescue for life surgery or necessary procedure in complex pathologies that require prolonged intubation and/or assisted ventilation.

Its execution is limited (especially in children) in specialized centers and in general anesthesia. Usually, it needs 24–48 h recovery in intensive care for a strict early observation.

Despite the demanding procedure, in most cases, it is not so difficult when it happens in intubated patient. Instead, when it occurs in an emergency, in uncomfortable conditions, and in non-intubated patient, it represents a challenging surgery burdened with many risks also for a skilled team.

In most cases, the subject recovery is good and quite fast, and he can surprisingly adapt to the new situation.

The aphonia, which is usually the main problem for the patient, is generally solvable through different devices such as the phonatory valve (except in cases with large amputation of the larynx or the vocal fold tissue). The dysphagia and the difficulty to perform abdominal contractions (Valsalva's maneuver) are usually transient and not serious problems.

Today, on the market, we can find a big variety of cannulas and other devices of any length, dimension, and diameter that may satisfy every need. Particularly, I would mention, in very complicated cases, tailored soft cannulas with devices (such as adjustable flange) that may adapt to almost any needs of the patient trachea.

In conclusion, the life of tracheostomized subjects is nowadays easier, and they can live, and not only survive, in a quite sufficient way even if their inability persists, obviously, to be serious.

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Cystic Mediastinal Masses in Children

15

Michele Torre, Federico Palo, and Vittorio Guerriero

15.1 Introduction

Mediastinal masses in children are rare, consisting of a varied group of entities including congenital, infectious, and neoplastic lesions. According to the size of the mass, we can observe both small asymptomatic lesions and large lesions that may cause airway compression. Patients with large mediastinal mass typically present with respiratory symptoms. Both benign and malignant tumors occur in the mediastinum and include neurogenic tumor, lymphoma, germ cell tumor, thymoma, lipoma, etc.

Main cystic lesions of the mediastinum include bronchogenic cyst, thymic cyst, cystic lymphangioma, and esophageal duplication cyst.

Large cystic tumors are more likely to cause airway compression in children than adults because of the small size and more compressibility of the trachea. For this reason, prompt management of these lesions is necessary to avoid respiratory impairment [1].

Thoracic tumors can be incidentally diagnosed without clinical symptoms or can be associated with various signs and symptoms, such as fever, cough, pneumonitis, chest pain, and a chest wall mass, or symptoms related to compression of adjacent structures such as the airway, esophagus, or superior central venous system. Compression of airway or mediastinal vasculature can be a life-threatening complication. Diagnostic evaluation usually starts with chest radiography. However, computed tomography (CT) (Fig. 15.1) and/or magnetic resonance imaging (MRI) is usually needed. CT is most indicated for parenchymal lesions, while MRI better investigates soft-tissue and cystic lesions, vascular anatomy, and posterior mediastinum tumors [2].

Standard treatment for cystic thoracic tumors in children consists of surgical resection. The traditional approach foresees thoracotomy or sternotomy (Fig. 15.2), but thoracoscopic technique is well established, both for diagnosis and treatment of mediastinal masses, and may be particularly useful in some cases, like benign neurogenic tumors of the posterior mediastinum [2].

15.2 Thymic Cyst

Thymic cysts are uncommon among the pediatric population, consisting of about 1% of all mediastinal masses. They can be divided into congenital and acquired lesions [3]. The median age of presentation is between 2 and 15 years, although they rarely present in adults [4].

M. Torre (✉) · V. Guerriero
Pediatric Airway Team, IRCCS Giannina Gaslini Genoa, Genoa, Italy
e-mail: micheletorre@gaslini.org; vittorioguerriero@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_15

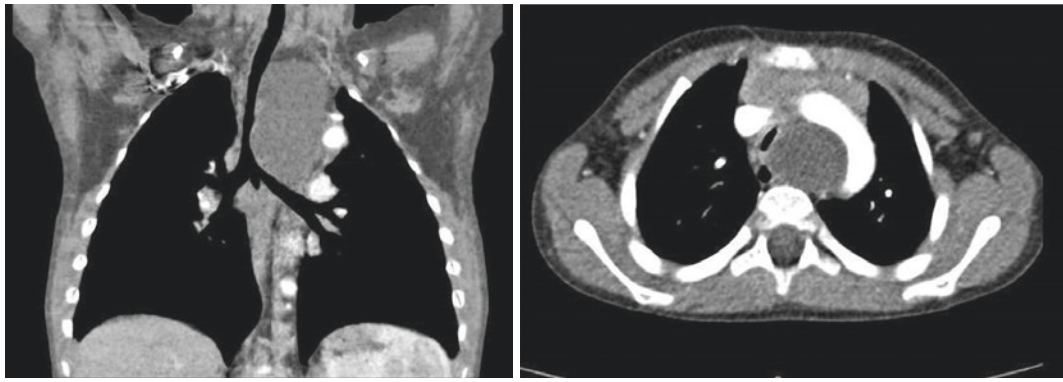

Fig. 15.1 mediastinal cyst, corresponding to a foregut duplication cyst: coronal and axial CT scan

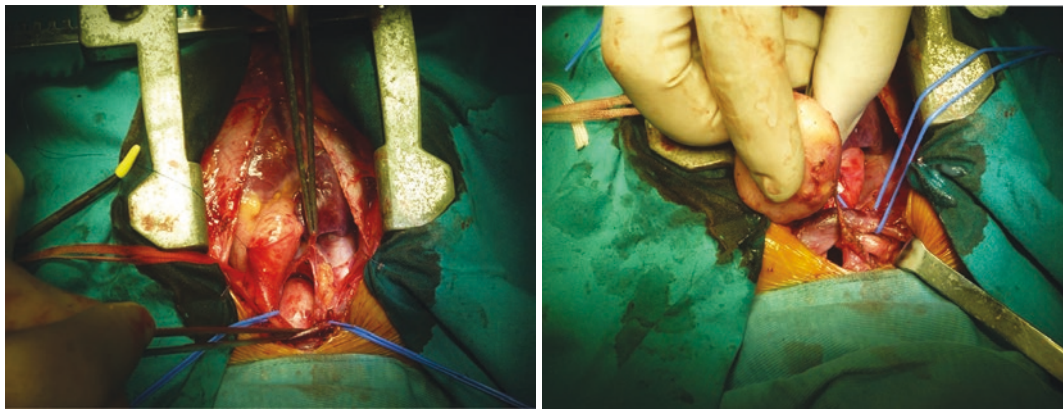

Fig. 15.2 surgical approach through sternotomy; removal of the cyst

Congenital cysts consist of a remnant of the thyropharyngeal duct, while those acquired may develop after radiotherapy in case of lymphoma or as inflammatory cysts seen in the context of autoimmune disorders; furthermore, they may also arise after thoracotomy procedures or may be associated with thymic tumors that can cause distortion or compression of normal thymic parenchyma [3].

Cysts may occur anywhere along the thyropharyngeal duct, from the pyriform sinus to the anterior mediastinum, but they are typically found in the lateral infrahyoid neck, with an intimate association with the carotid sheath, connected to the mediastinal thymus directly or by a fibrous cord.

Thymic cysts are usually asymptomatic; however, symptoms like dysphagia, respiratory distress, or vocal cord paralysis may be observed in the case of large lesions [4].

Thymic cysts are usually composed of a single large dominant cyst, smooth and thin-walled, and may have mural nodularity; they are lined by ciliated epithelium, with the presence of lymphocytes, thymic tissue, cholesterol crystals, and Hassall corpuscles within the wall [2]. Larger thymic cysts may present as dumbbell-shaped cervicothoracic masses, with the cyst passing through the thoracic inlet from the lower lateral neck into the superior mediastinum [4].

When a thymic cyst is suspected, ultrasonography (US), CT, and MRI are useful imaging investigations. US may be performed to characterize the fluid-filled mass, although CT and MRI have superior sensibility in showing the extent of the lesion and its relationship with the mediastinal

structures [2]. Needle aspiration has been an alternative proposed technique for making the diagnosis, but examination of surgically resected specimens is mandatory for diagnosis. Differential diagnoses of cervical thymic cyst include thyroglossal duct cyst, branchial cleft cyst, laryngocele, lymphovascular malformations, benign tumors (dermoid and epidermoid cysts), and malignant tumors [3].

Radical surgical excision allows an excellent prognosis [2].

15.3 Bronchogenic Cyst

Bronchogenic cysts are the result of an abnormal budding of the tracheal diverticulum during the formation of the foregut. They are more frequent in males and can be located anywhere along the tracheoesophageal tree, although they tend to occur near the carina or right paratracheal regions. Intrapulmonary location accounts for about 20% of the cases [4, 5]. Bronchogenic cysts may be considered a part of a spectrum of anomalies, linked to anomalous lung and foregut development. These sometimes share some characteristics and histologic findings and include congenital cystic adenomatous malformation (CCAM), bronchopulmonary sequestrations, congenital lobar emphysema, bronchogenic cysts, esophageal duplication cysts, and neurenteric cysts. Some authors have proposed the term bronchopulmonary-foregut malformations to enclose all these anomalies [2].

In many cases, bronchogenic cysts are asymptomatic, and the discovery is incidental on chest radiography, or as a space-occupying lesion or as a cyst with an air-fluid level. They become symptomatic concurrently with the impairment of the airway or airway/lung infection. Airway obstruction is more typically seen in infants, while infection tends to present in older children. Symptoms related to airway alterations include stridor, wheezing, cough, nasal flaring, retractions, and intermittent cyanotic spells. Symptoms related to infection include fever, cough, hemoptysis, and recurrent pneumonia. Communication with the airway is rare, but they may tightly close to it. There may also be associated vertebral anomalies [6]. CT demonstrates in most cases a spherical nonenhancing mass of variable attenuation with sharp borders. An air-fluid level is rarely present if there is open communication with the airway [5].

Visualization of respiratory epithelium on histology sample allows the definitive diagnosis of bronchogenic cyst [4]. The cysts are lined with respiratory tract ciliated columnar epithelium or cuboidal epithelium containing mucus glands [5–7].

Cysts are typically radically excised for diagnosis when discovered. Infectious complications are thought to be frequent enough to indicate elective excision. If a cyst presents acute infection, surgery should be delayed to start antibiotic treatment [2–8]. The procedure could be performed either by video-assisted thoracic surgery or by lateral thoracotomy, depending on the complexity of the cyst and the experience of the surgeon [2–5].

15.4 Esophageal Duplication Cyst

Esophageal duplication cysts are discussed in the chapter related to the esophagus.

15.5 Lymphangioma

Lymphangiomas, well known as microcystic/macrocystic lymphatic malformations, are congenital lesions that are characterized by an abnormal proliferation of lymphatic and vascular tissue. They occur in about 1 in 6000 births, and only about 1% are limited to the thoracic cavity [2]. Large cervical lymphatic malformations, however, may extend into the mediastinum in 2% up to 10% of cases [2]. Most lymphatic anomalies present in the first years of life. They are often asymptomatic, and they may present with dyspnea when compressing the airway or other vital mediastinal structures [4].

These malformations are mostly composed of large lymphatic cysts; they can also consist of thicker tissue with more prominent vascular elements. Lymphatic tissue has a thin endothelial

lining and may also contain smooth muscle cells. Isolated thoracic lymphangiomas are usually found in the anterior mediastinum, although they can be found in other compartments and the lung tissue as well. Cervical lymphangiomas sometimes extend into the posterior mediastinum [2].

Thoracic lymphatic malformations are often incidental findings on chest imaging. Symptoms, when present, are secondary to airway, lungs, or other mediastinal structures compression by the mass. They include cough, stridor, dyspnea, dysphagia, hemoptysis, superior vena cava syndrome, and Horner syndrome. Infection or collection of chyle in the pleura or pericardium may occur. Intralesional bleeding with rapid enlargement of the mass and sudden onset of symptoms has been described [2].

Thoracic lymphangiomas appear as homogeneous masses on chest radiography. US shows a lesion that is primarily cystic, sometimes containing debris or other signs of recent bleeding.

A CT or MRI image could be visualized enhancement of internal septa and cyst wall, without enhancement of central portions. When a hemorrhage or infection occurs, proteinaceous material within the cysts can be produced, and consequently, lymphatic malformation appears as a more complex fluid collection instead of a simple fluid-filled cystic mass [4].

The optimal therapy for symptomatic mediastinal lymphangiomas is radical excision, but it is widely agreed that vital structures should not be sacrificed during the procedure. Because often pathologic tissue remains after surgery and some lesions are simply not resectable because they involve vital structures, alternative strategies for therapy have been advanced. Intralesional injection of sclerosing agents is often used as a primary or secondary therapy [2].

15.6 Pericardial Cysts

Pericardial cysts arise in case of mesodermal lacunae fail to coalesce during pericardium development. These cysts are typically located at the cardio-phrenic angle in the middle mediastinum and are thin-walled with a flat mesothelial lining. Pericardial cysts are usually found incidentally on chest images. Because of the benign histology and the absence of symptoms, some investigators believe that the approach of pericardial cysts is observation. However, others authors, for their potential symptomatology, such as inflammation, justify surgical excision. In fact, cardiac tamponade, attributable to hemorrhage or effusion, has been reported. US and CT usually confirm the diagnosis. Surgical excision is usually safe and can be performed by thoracotomy or a thoracoscopic approach [2].

15.7 Neurenteric Cyst

Neurenteric cysts are rare congenital lesions resulting from the abnormal separation of gastrointestinal tract from the primitive neural crest. They are most commonly located in the posterior mediastinum and the spinal canal can be involved. Congenital vertebral anomalies such as spinal dysraphism are classically associated with neurenteric cysts [2].

Neurenteric cysts can be detected in any age-group (usually discovered during the first 5 years of life) and can be found anywhere from head to abdomen, but they are often located in the posterior mediastinum [9].

In the pediatric population, one-third of the patient with mediastinal cysts remains asymptomatic, while two-third present with alterations of the respiratory system. These cysts are usually benign, but due to their size, they can cause compression of the adjacent structures [9].

In case of respiratory symptoms or distress, neurenteric cyst is suggested by a chest radiograph showing cervical or thoracic vertebral anomalies and a posterior mediastinal cyst. Both CT and MRI have great sensibility in diagnosing the condition. Histologically, both neural elements and gastrointestinal epithelium are typically seen [4].

Neurenteric cysts can present with a broad spectrum of signs and symptoms and can be life-threatening. When the gastric epithelium lines the cyst, hemorrhage, anemia, and pain can be the

principal symptoms. The majority of children with these cysts presents with central nervous system symptoms, such as back pain, sensory/motor deficit, or gait disturbances.

Complete surgical resection by thoracotomy or thoracoscopy of these lesions is feasible. If an asymptomatic or less symptomatic lesion is discovered, elective excision is recommended if operative risks are not too high [9].

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Congenital Lung Malformations

16

Francesca Rizzo, Michele Torre, Vittorio Guerriero, Federico Palo, and Fiammetta Sertorio

16.1 Introduction

Congenital lung malformation (CLM) represents 5–18.7% of all congenital anomalies; this range may be underestimated because of many undetected or asymptomatic lesions.

Annual incidence is 30–42 cases/100,000 population.

Defective budding, differentiation, and separation of the primitive foregut, between 24 and 36 days of gestation, is considered the main cause for the appearance of congenital pulmonary malformations. Other mechanisms can be airway obstruction, vascular abnormality (including absent pulmonary artery associated with pulmonary agenesis), and genetic mechanisms like those leading to impairment in the signaling pathways responsible for airway development. The complexity and diversity of congenital pulmonary malformations point to a likely multifactorial etiology, with a combination of different factors.

Clinical presentation varies widely from respiratory distress at birth, recurrent infections in older children, to incidental detection in asymptomatic adults.

CLM includes parenchymal, vascular, bronchial, and foregut anomalies, and they can show predominantly parenchymal or predominantly vascular anomalies or a combination of both. They can be classified as involving only one component, i.e., congenital lobar emphysema (CLE) (parenchymal abnormality), arteriovenous malformation (vascular abnormality), foregut duplication cyst (foregut anomaly), bronchial atresia (airway anomaly), or including two or more components (pulmonary sequestration is a complex malformation that has both pulmonary and vascular anomalies in association).

Recognizing the antenatal and postnatal imaging features of these abnormalities is necessary for optimal prenatal counseling and appropriate peri- and postnatal management.

US is the first imaging tool used for fetal screening, and it is able to provide valuable information about the presence and size of a focal lung lesion and its effects on adjacent structures.

F. Rizzo
Radiology Unit, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: francescarizzo@gaslini.org

M. Torre (✉) · V. Guerriero
Pediatric Thoracic and Airway Surgery Unit, IRCCS Giannina Gaslini Genoa, Genoa, Italy
e-mail: micheletorre@gaslini.org; vittorioguerriero@gaslini.org

F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy

F. Sertorio
Radiology Unit, IRCCS Giannina Gaslini, University of Genoa, Genoa, Italy

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_16

Fetal MRI allows both lesion evaluation and lung volume quantification.

Postnatal chest X-ray remains very helpful for the screening of asymptomatic and symptomatic patients, while CT and MRI confirm and further characterize the congenital pulmonary malformations.

16.2 Bronchial Atresia

Definition: Bronchial atresia is due to focal stenosis or obliteration of subsegmental, segmental, or lobar bronchus with peri-bronchial emphysema due to hyperinflation and distal mucoid impaction (mucocele/bronchocele). It occurs between 5th and 15th weeks of gestation. The upper lobe is most frequently affected, while the involvement of the middle and lower lobe is rare. Bronchial atresia can be found associated with other abnormalities such as intra-lobar PS (pulmonary sequestration), CPAM (congenital pulmonary airway malformation), and CLE (congenital lobar emphysema) [1, 3].

Clinical presentation: Bronchial atresia is often asymptomatic and can be diagnosed incidentally even in adults. In some cases, children can present with recurrent respiratory tract infections, chronic cough, dyspnea, and/or wheezing.

16.2.1 Diagnosis

Prenatal US: Oval, tubular branching structure of increased echogenicity in the lung.

Prenatal MR: Solid lung mass characterized by homogenous high signal intensity on T2-weighted images.

Chest X-ray: Round or oval opacity in the apical or apical posterior segment of the upper lobe, due to the mucus accumulated inside a bronchus (mucocele).

MDCT: demonstrates the dilated round, oval, or tubular-shaped bronchial mucocele adjacent to a hyperinflated area with decreased vascularity. Expiratory images confirm air-trapping.

Differential Diagnosis: Congenital Lobar over-inflation (CLO), Congenital Pulmonary Airway Malformation (CPAM), Bronchogenic Cyst, Bronchopulmonary Sequestration, Allergic Bronchopulmonary Aspergillosis, Slow-Growing Endobronchial Tumor [1–3] (Fig. 16.1).

Air-trapping in the superior segment of the right lower lobe due to mucoid impaction in the bronchus distal to the atretic bronchial segment.

16.2.2 Management

Conservative treatment with regular chest radiograph follow-up. Surgical resection is reserved

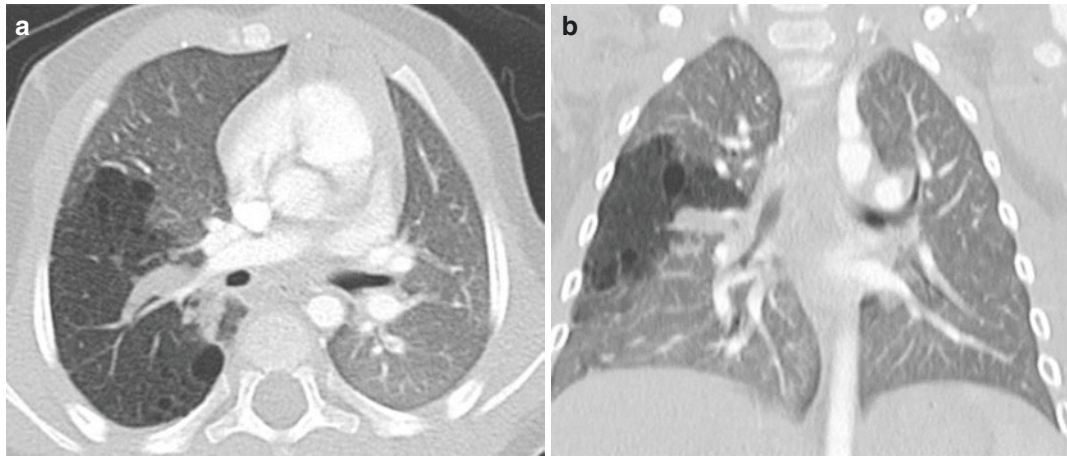

Fig. 16.1 Patient with Bronchial atresia. CT angiography: (**a**) axial image, (**b**) coronal image

for patients with repeated infections (possibly mini-invasive thoracoscopic surgery and limited resection).

16.3 Bronchogenic Cyst

Definition: Developmental anomaly due to the abnormal budding of the tracheobronchial tree during airway development (26–40 days of fetal life). This supernumerary bud differentiates into a blind-ending pouch that is typically filled with mucus. It is part of a spectrum of foregut duplication cysts including enteric cysts and neuroenteric cysts. In all, 85% of the cysts are in the mediastinum (subcarinal, hilar, and right paratracheal location). Pulmonary cysts in many cases are in lower lobes and are better classified as congenital or acquired mucocele/sequestration. Rare locations: neck, pericardium, abdominal cavity. The content may be air, fluid, or both.

Clinical presentation: in many cases, bronchogenic cysts are found incidentally. The symptomatic pediatric patient may present with chest pain, recurrent infections, dysphagia, and respiratory distress due to a mass effect with compression of the esophagus and/or airway. Mediastinal bronchogenic cysts have no bronchial communication. Intraparenchymal bronchogenic cysts have bronchial communication, and they may become infected especially in older children [4–8].

16.3.1 Diagnosis

Chest X-ray: Round or oval, well-delimited, not calcified mass in the middle mediastinal compartment, air-filled (lucent) or with an air-fluid level.

US: Round mass with posterior acoustic enhancement, thin wall with variable echogenicity of internal contents. No internal vascularity at Color Doppler evaluation.

CE MDCT: Well-defined lesions with fluid density with higher attenuation than water due to proteinaceous debris from mucoid material or previous hemorrhage.

MRI: High signal intensity on T2-weighted images, variable signal on T1-weighted images depending on the internal content, no diffusion restriction on DWI sequences. T2-weighted Fat Sat or STIR sequences are used to maximize the contrast of cyst fluid against surrounding tissues.

Usually, no contrast enhancement on CT or MRI following contrast medium administration, apart from minimal enhancement of the cyst wall and surrounding tissues in case of concomitant infection.

Differential Diagnosis: Neurenteric Cyst, enteric duplication, Round Pneumonia, Neuroblastoma, Lymphadenopathy, Lymphatic Malformation, Congenital Pulmonary Airway Malformation, Bronchopulmonary Sequestrations [4–8].

16.3.2 Management

Surgical resection is recommended in children; conservative treatment in adults or children considered to be at high surgical risk. Percutaneous or transbronchial needle aspiration to reduce the mass effect and help minimize surgical incision length during subsequent resection.

16.4 Congenital Pulmonary Airway Malformation (CPAM)

Definition: Heterogeneous group of cystic and non-cystic lung lesions resulting from early airway maldevelopment characterized by the proliferation of distal airway-like structures with the suppression of normal alveolar formation, resulting in a frequently (but not exclusively) cystic gross appearance. The term CPAM is now preferred to CCAM (congenital cystic adenomatoid malformation), as some lesions may not be cystic or adenomatoid at all. CPAM is the most common congenital lung malformation (incidence 1:25,000, 1/35,000 live births; 30–47% of fetal thoracic lung lesions). Strong association of CPAM with bronchial atresia makes the postulated etiology of intrauterine obstruction of the airway well accepted.

Location: CPAM is usually unilateral and limited to a single lobe in 95% of cases, without lobar predilection. Vascularization is provided by the pulmonary arteries, and drainage occurs through the pulmonary veins (as for the normal lung parenchyma). Communication with the bronchial tree is uncommon.

Clinical presentation: CPAM may cause respiratory distress in the newborn (25% of cases, depending on lesion size, mediastinal shift, hydrops) or recurrent lung infections in older children.

There are five histopathological types of CPAM (Stocker classification): acinar dysgenesis or dysplasia of the trachea or bronchus involving all lung lobes (type 0), incompatible with life; single or multiple large cysts (3–10 cm) (type 1), numerous small cysts (0.5–2 cm) (type 2); solid "adenomatoid" tissue with small cysts <0.5 cm with a markedly increased size of the lobe or lung (type 3); large peripheral air-filled cysts with mass effect (type 4) [8–16].

16.4.1 Diagnosis

By imaging, CPAM is generally divided into large cyst, small cyst, microcystic/solid, or mixed types.

Chest X-Ray: typically shows multiple air-filled, thin-walled cysts of varying size. At birth, the cysts are fluid-filled, but later, as they aerate, air-fluid levels appear. The type 4 CPAM usually presents very large cysts with lobar expansion or sometimes with pneumothorax, causing mass effect and mediastinal shift. A cystic PPB (pleuropulmonary blastoma) may be quite similar to CPAM 1 and 4. In many cases, postnatal chest radiography may be normal despite a correct prenatal diagnosis of CPAM, because of complete or partial regression of the cysts. (Fig. 16.2a).

CE MDCT: can be performed to determine the extension of the residual lesion and for the evaluation of the systemic feeding vessels before surgery. (Fig. 16.2b–d).

MRI: prenatal evaluation of the lesion patterns, like hypoplasia of remaining lungs, mass effects, and other anomalies. On T2w SSFSE sequence, solid/microcystic lesions are hyperintense compared to the normal lung parenchyma, cystic lesions have fluid signal intensity; lower lesion signal may be due to regression.

Differential diagnosis: Bronchopulmonary Sequestration, Congenital Diaphragmatic Hernia, Bronchogenic cyst, Pleuropulmonary Blastoma, Cavitary Necrosis/Abscess Complicating Pneumonia, Congenital Lobar Over-inflation, Persistent Pulmonary Interstitial Emphysema [8–16].

16.4.2 Management

For asymptomatic infants and children, there is no real consensus on indications and timing for surgery. Prenatally detected lesions are followed with ultrasound and/or MRI. More clear-cut indications for surgical resection may include recurrent infections, complications, and an uncertain differential diagnosis between CPAM and PPB.

16.5 Congenital Lobar Emphysema

Definition: Progressive lobar hyperinflation anomaly due to overdistension of the alveoli also known as congenital lobar over-inflation (CLO) or infantile lobar emphysema. It can be associated with intrinsic and/or extrinsic bronchial obstruction or a defect in bronchial wall anatomy and structure. The incidence is 1/20,000–1/30,000 live births. There are two types of CLE: hypo-alveolar type, with less than normal but quite dilated alveoli, and poly-alveolar type, with normal size alveoli whose number is increased, compared to normal lung parenchyma. The left upper lobe is the most frequently affected (42%), followed by the right middle (35%), and right upper lobe (21%). Multifocal or bilateral involvement is rare.

Clinical presentation: Hypo-alveolar type CLE usually presents in the first 6 months of life with respiratory distress due to mass effect with compression on adjacent lung and mediastinal structures by the hyperinflated lung lobe (Fig. 16.3) [2, 8, 17–20].

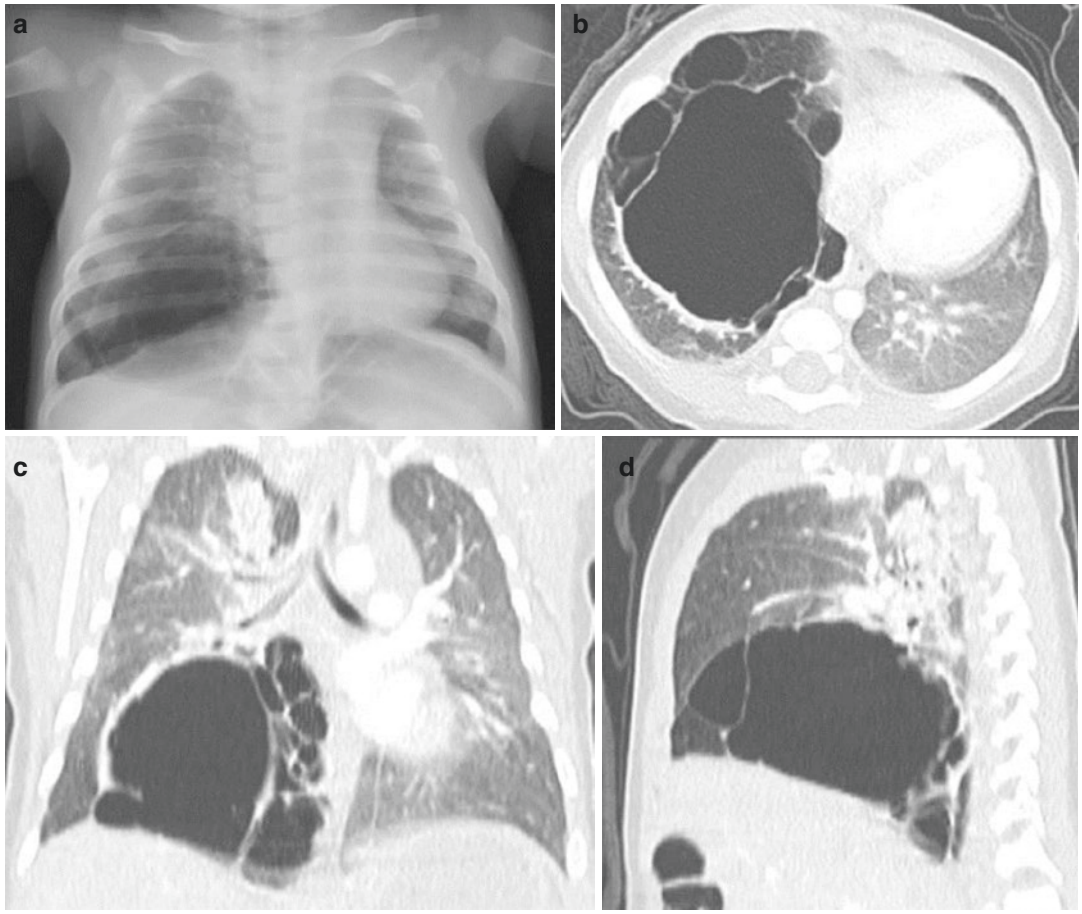

Fig. 16.2 Patient with type 2 CPAM. (**a**) RX; (**b–d**) CT angiography axial, coronal, sagittal image: right cystic mass with septa causing controlateral mediastinal shift

16.5.1 Diagnosis

Chest X-Ray: Radio dense lobe becomes progressively hyperlucent and hyperexpanded due to the initial fetal lung fluid retention and progressive parenchymal hyperinflation, which cause mass effect on the adjacent lung and mediastinal structures. X-ray may have a reticular pattern as fluid clears through distended lymphatics.

CE MDCT: visualization of attenuated vessels indicative of reduced vascularity within the overinflated lung segment, with effacement of adjacent structures and mediastinal shift. Contrast medium is used to evaluate vascular structures and other abnormalities (e.g., sequestration).

Differential Diagnosis: Pneumothorax, Persistent Pulmonary Interstitial Emphysema, Pulmonary Hypoplasia, Swyer-James Syndrome, Bronchial Atresia, Congenital Pulmonary Airway Malformation [2, 8, 17–20].

16.5.2 Management

Asymptomatic or mildly symptomatic patients can be managed conservatively, as spontaneous size reduction of the lesion can occur. For symptomatic children, lobectomy is the current approach, either open or thoracoscopic.

16.6 Pulmonary Sequestration (And Hybrid Lesion)

Definition: nonfunctional lung parenchyma, without connection with the tracheobronchial tree and pulmonary arteries. It receives blood

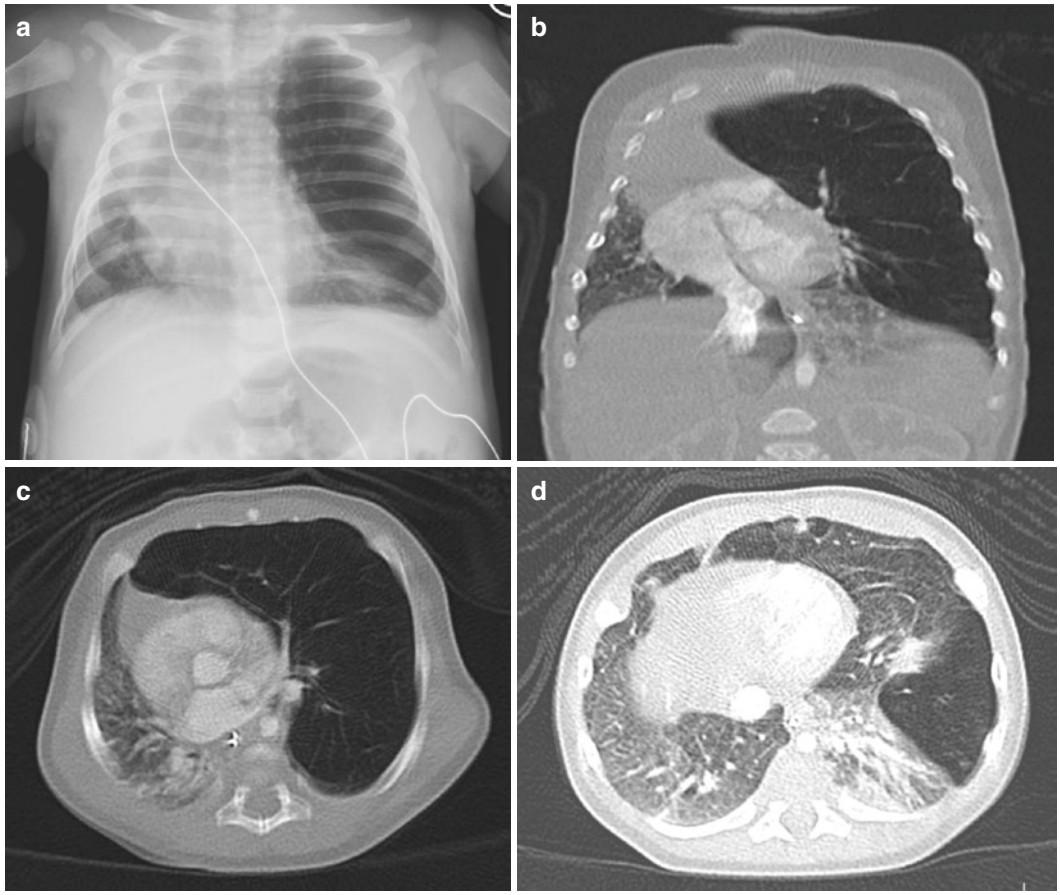

Fig. 16.3 Patient with left Congenital Lobar Emphysema. (**a**) RX: hyperinflation of most of the left lung associated with a right mediastinal shift. (**b**) Coronal and (**c**, **d**) axial MPR (multiplanar reconstruction): left upper lobe hyperinflation associated with sub-atelectasia of the left lower lung lobe parenchyma and right mediastinal shift

supply from a systemic artery. Pulmonary sequestration is due to abnormal budding of the primitive foregut and is often associated with bronchial atresia. There are two types of pulmonary sequestration:

- Intralobar pulmonary sequestration (ILS: 75% of cases): It lies within the visceral pleura, is strictly connected to the adjacent lung, and usually occurs in the postero-basal segment of the lower lobe. It receives blood from a systemic artery originating in the thorax or the abdomen. The venous blood drains in the inferior pulmonary vein and goes to the left atrium. Intralobar sequestration communicates with adjacent lung parenchyma through the pores of Kohn, which allow infected mucus, when present, to reach the abnormal lung parenchyma. When this happens, resolution is incomplete or slow because of inadequate bronchial drainage.
- Extra-lobar pulmonary sequestration (ELS, 25% of cases): It is enveloped by its pleura and is located near the left lower lobe. The arterial supply is through a systemic artery arising in the thorax or abdomen, while the venous drainage occurs through a systemic vein, with the potential for substantial arteriovenous shunting leading to high output cardiac failure. Almost 80% of extra lobar sequestrations are located near the left lower lobe, and 10% is infra-diaphragmatic in position. ELS is commonly associated with other malformations such as diaphragmatic defects,

chest wall and vertebral deformities, hindgut duplication, and congenital heart disease.

Both intralobar and extralobar sequestration may show the same parenchymal alterations of CPAM: In those cases, they are defined as "hybrid lesions" caused by bronchial atresia, which is common to PS and CPAM.

Clinical presentation: ELS is often asymptomatic postnatally; it may cause neonatal respiratory distress due to mass effect or adjacent pulmonary hypoplasia. ILS presents with recurrent pneumonia symptoms in an older child/adult [8, 10, 12, 21–26].

16.6.1 Diagnosis

Chest X-Ray: varies according to the type, the presence or not of concomitant malformations (i.e. CPAM like hybrid lesion), the presence of superimposed infection. The usual radiography shows a persistent lower lobe opacity adjacent to the diaphragm. Cystic areas, air or fluid-filled, can be seen (hybrid lesions).

US (pre and postnatal): Pulmonary sequestration is seen as a homogeneous mass most commonly located at the lung base, echogenic, round, oval, or triangular, adjacent to the diaphragm. On Doppler US examination, a systemic feeding vessel can be appreciated.

CE MDCT: It is recommended for all congenital lung lesions to evaluate systemic vascular supply prior to surgery. It shows heterogeneously enhancing solid lung parenchymal mass (classic form) or cystic lesion sometimes with internal air-fluid levels (hybrid lesion), usually on the lower lobe, or rarely below the diaphragm. ELS may twist, thrombose, or bleed, making diagnosis more difficult. The systemic arterial supply can be identified originating from the thoracic or abdominal aorta. CT detects also associated malformation (Figs. 16.4, 16.5, 16.6, and 16.7).

MRI: It differentiates the content of the lesion as solid, cystic, hemorrhagic, or containing mucous components. Lesions are most frequently homogeneous, hyperintense on T2w sequences. They can appear solid with cystic components in hybrid lesions. The feeding artery is visualized as flow void on SE/FSE sequences and maybe bright on some GRE sequences.

Differential diagnosis: Chronic Lung Opacity, Anomalous Systemic Blood Flow to Lung, Focal Chest Mass (e.g., CPAM, Bronchogenic cyst,

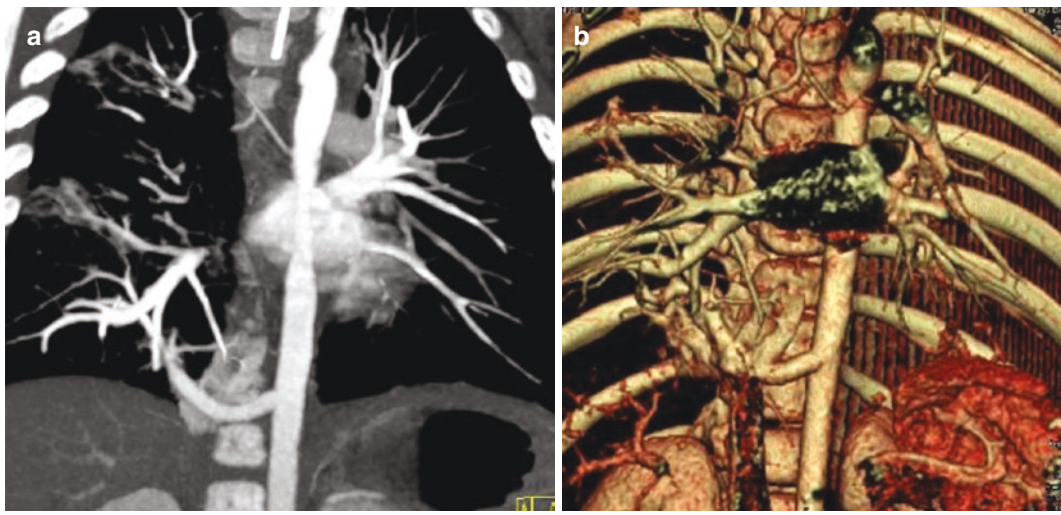

Fig. 16.4 6 Patient with intralobar Sequestration. CT angiography (**a**) coronal MIP (maximum intensity projection); (**b**) coronal volume rendering reconstruction. Small mass in the right lower lobe; anomalous artery originating from the descending aorta whit venous drainage into the right inferior pulmonary vein

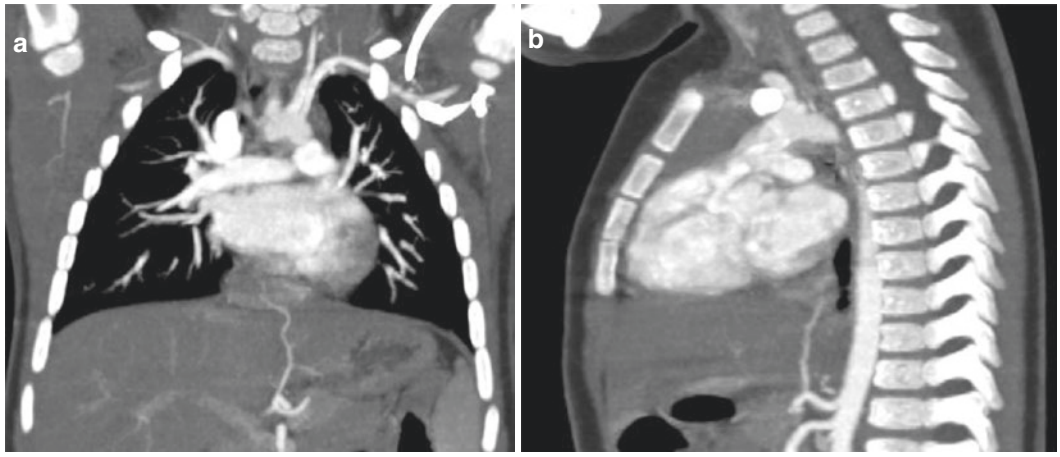

Fig. 16.5 Patient with intra-lobar Sequestration. CT angiography (**a**) coronal and (**b**) sagittal MIP (maximum intensity projection). Small mass in the right lower lobe; anomalous artery originating from the celiac tripod

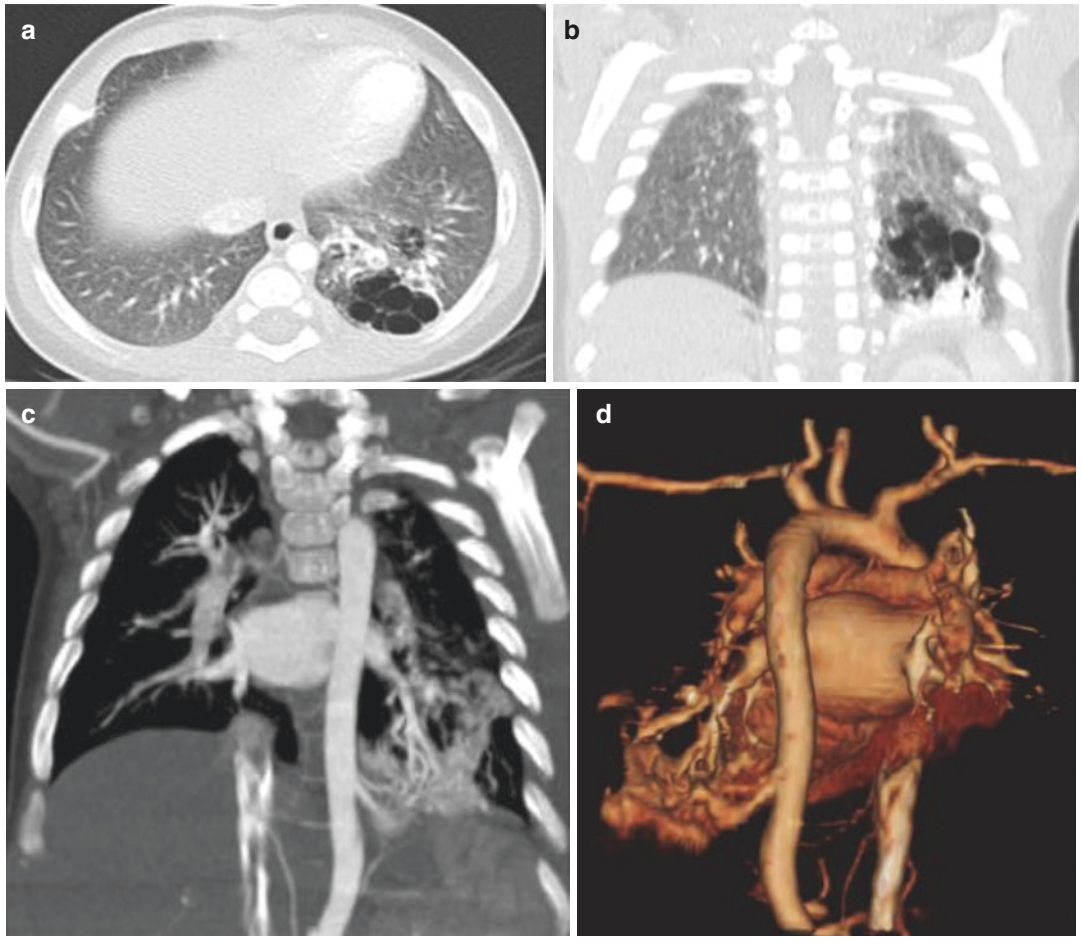

Fig. 16.6 Patient with hybrid CPAM-Sequestration. CT angiography (**a**) axial, (**b**) coronal MPR (multiplanar reconstruction): images show small cystic lesions of the parenchyma of the lower left lobe associated with a solid basal lesion. (**c**) coronal MIP (maximum intensity projection); (**d**) volume rendering reconstruction: Anomalous artery originating from the descending aorta whit venous drainage into the left inferior pulmonary vein

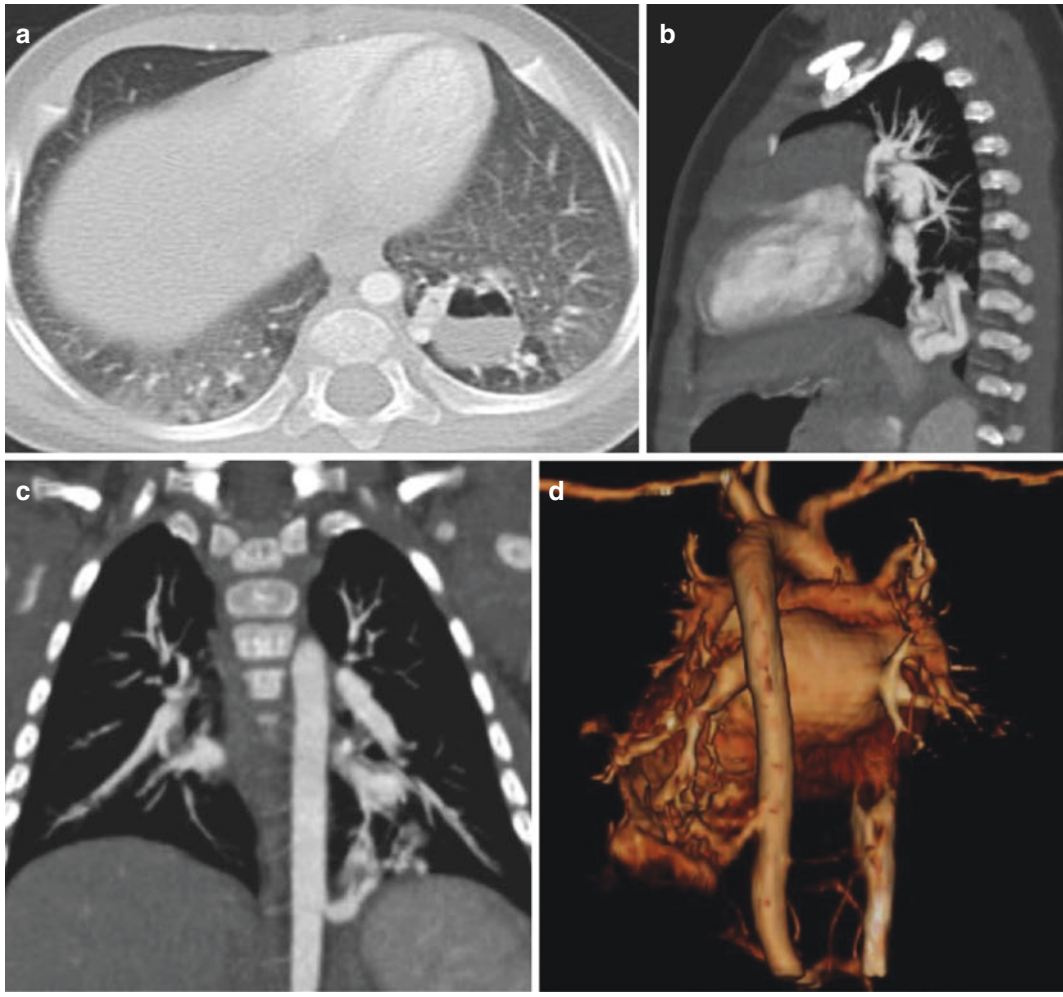

Fig. 16.7 Patient with hybrid CPAM-Sequestration. CT angiography (**a**) axial MPR (multiplanar reconstruction): intraparenchymal fluid cyst with an air-fluid level in the posterior-basal segment of the left inferior lobe. (**b**) sagittal MIP (maximum intensity projection); (**c**) coronal MIP; (**d**) volume rendering reconstruction, anomalous artery originating from the descending aorta with venous drainage into the left inferior pulmonary vein

Round pneumonia, Lymphatic malformation), Solid Suprarenal Mass (e.g., neuroblastoma) [8, 10, 12, 21–26].

16.6.2 Management

Surgical resection for PS with recurrent infections. Embolization of the feeding artery is an option, with a reported high success rate. Management of asymptomatic cases is controversial: elective surgical resection versus monitoring.

16.7 Surgical Management of CLM

Most CLMs have a favorable prognosis, with a survival rate >95%, but in some cases, there is a risk of antenatal and postnatal complications. In case of antenatal complications, the possible therapeutic options are thoracentesis, pleuroamniotic shunt placement, percutaneous ultrasound-guided sclerotherapy, or radiofrequency/laser ablation, fetal bronchoscopy, and rarely open fetal surgery; none of these procedures

are evidence-based and all should be considered the last option [27].

If postnatal complications occur, the child should first be stabilized as far as possible and then therapeutic decisions are taken.

In the case of asymptomatic neonates, the timing and necessity of surgical resection of CLM is still a source of controversy. Approximately in 10–30% of asymptomatic neonates will occur an infection during the first year of life; the presence of infectious symptoms is linked with higher rates of intra- and postoperative complications and longer hospitalization [28].

Actually, CLMs are removed by video-assisted thoracoscopy (VATS) or by robotic-assisted thoracoscopy (RATS) (Fig. 16.8) in some patients, a safe and feasible alternative to open thoracotomy. Minimally invasive techniques (VATS and RATS) are usually uncomplicated; compared to open surgery, these procedures are preferred because of smaller incisions with obvious cosmetic benefits, less pain, lower complication rates, and shorter hospital stays although with longer operative time [27]. Moreover, the imagined magnification provided by thoracoscopy allows for significantly better discrimination between normal and pathologic lung and clearer visualization of fissures and vascular structures.

The most important risk factor for conversion to open thoracotomy is the history of respiratory symptoms and infection, which can produce intrathoracic adhesions and a subsequently more difficult dissection [28].

Most cases of parenchymal CLM needing surgery require lobectomy in order to prevent postoperative air leaks, residual disease, and perhaps reduce the risk of malignant degeneration.

On the other hand, lung-sparing approaches such as segmentectomy have been indicated for small and well-defined segmental lesions as well as in cases with the bilateral or multilobar disease. In some cases, the presence of malignancy has been described even after apparent complete resection of a CLM, in the same or different lung segment, but it is possible that CLM was indeed neoplastic from the beginning [27].

After induction of anesthesia and administration of prophylactic antibiotics, the surgical procedure begins. Placement of three to four thoracoscopic trocars is needed to access the thoracic cavity. The lobar dissection begins with mobilization of the lung, releasing the inferior pulmonary ligament and any pleuropulmonary

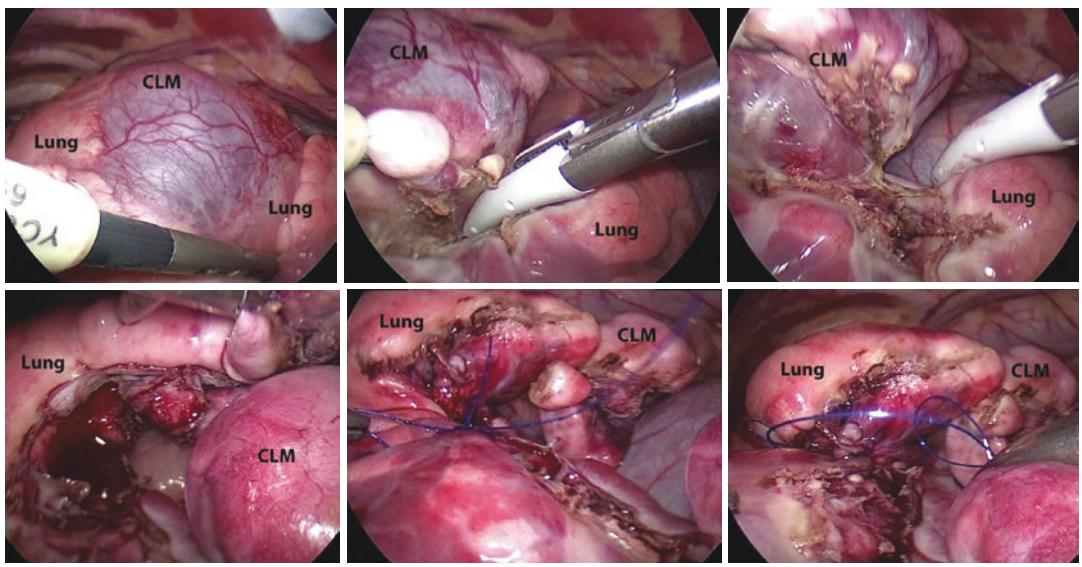

Fig. 16.8 Photo-sequence of a thoracoscopic procedure for the resection of CLM

adhesions. In case of intralobar bronchopulmonary sequestration, the systemic vascular supply (from thoracic or abdominal aorta) is identified, ligated, and divided.

Afterward, attention is turned to the hilum. The branches of the superior or inferior pulmonary vein are identified but not divided in order to avoid vascular congestion. Once isolated, the arterial branches to the specific lobe, and then the vein is sealed and divided. Middle lobectomies proceed first with completion of the fissures to allow identification of the branches of both the pulmonary vein and the artery, followed by isolation and division of segmental branches. At the end of the procedure, a thoracostomy tube is inserted and the lung is re-expanded under direct visualization. During thoracoscopic resection of CLM, both intraoperative and postoperative complications can occur. The most frequently described intraoperative complications include hemorrhage, requiring transfusion, bronchial injury, requiring repair, phrenic nerve injury, and incomplete resection of the lesion.

Common postoperative complications include pneumonia, persistent air leak/pneumothorax, and need for blood transfusion [28].

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Part V

Oesphagus and Diaphragm

Esophageal Atresia

17

Girolamo Mattioli and Federico Palo

17.1 Introduction

Esophageal atresia (EA) is the most common congenital defect of the esophagus in neonates secondary to a deviation from the normal embryonic development of the foregut. The overall worldwide prevalence of EA is estimated to be approximately 2.4 per 100.000 births [1, 2]. EA could be associated with other comorbidities that affect the esophagus, such as dysphagia, feeding difficulties, gastroesophageal reflux disease (GERD), and respiratory problems.

The improvement in survival observed in the past two decades is multifactorial and attributable to all the following factors: advances in neonatal intensive care and neonatal anesthesia, ventilatory and nutritional support, antibiotic therapy, early surgical correction, refinement of materials, and surgical techniques and multidisciplinary approach [3].

The newborn baby with atresia of the esophagus, who has no other abnormalities incompatible with life, has a survival rate of up to 95%, persisting a high incidence of complications early and late. Zimmer et al. report a reduction in mortality from 100% in 1941 to 9% today. [4]

G. Mattioli (✉) · F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini, University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

17.2 Embryology and Classification

The understanding of the embryological basis of these defects is still incomplete. The primitive digestive tube emerges from the primitive endoderm and subsequently gives rise to the esophagus and trachea. There are three different theories that try to define this malformation. The first theory postulates that the trachea derives from the evagination of a tracheal diverticulum from the primitive digestive tract that grows in a caudal direction with the resulting separation of the trachea and esophagus. Another theory holds that the formation of a mesenchymal septum in the coronal plane of the primitive digestive tube separates the trachea (ventral) and the esophagus (dorsal) from the distal to the proximal part of the digestive tube. In these theories, the origin of AE is determined by a failure of the separation mechanisms with cellular rearrangement of the distal part of the primitive digestive tract. The third theory is a combination of the previous ones and involves the formation of a tracheal diverticulum and a mesenchymal septum [5–11].

EA can occur with or without tracheoesophageal fistula (TEF), an anomalous connection between the trachea and the esophagus. The original classification by Vogt in 1929 is still used today and has been further revised by Ladd (1944) and Gross (1953) [12–14].

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_17

This classification divides the malformation into five types (Fig. 17.1):

- Type A: Esophageal atresia without fistula (pure esophageal atresia) 10%.
- Type B: Esophageal atresia with proximal TEF (<1%).
- Type C: Esophageal atresia with distal TEF (85%).
- Type D: Esophageal atresia with proximal and distal TEF (4%).
- Type E: TEF without atresia - "type H"—(4%).

The majority of these neonates (55%) present associated anomalies including vertebral, anorectal, cardiac, renal, radial, and/or limb abnormalities (VACTERL association), trisomy 18, or multiple other malformations. Infants with AE without fistula have a higher incidence of associated anomalies (65%). Moreover, 1% of newborns with EA have CHARGE syndrome, characterized by coloboma, heart defects, aortic coarctation or aberrant subclavian artery, atresia choanae, retarded growth and development, genital hypoplasia, and/or ear anomalies and/or deafness [12–20].

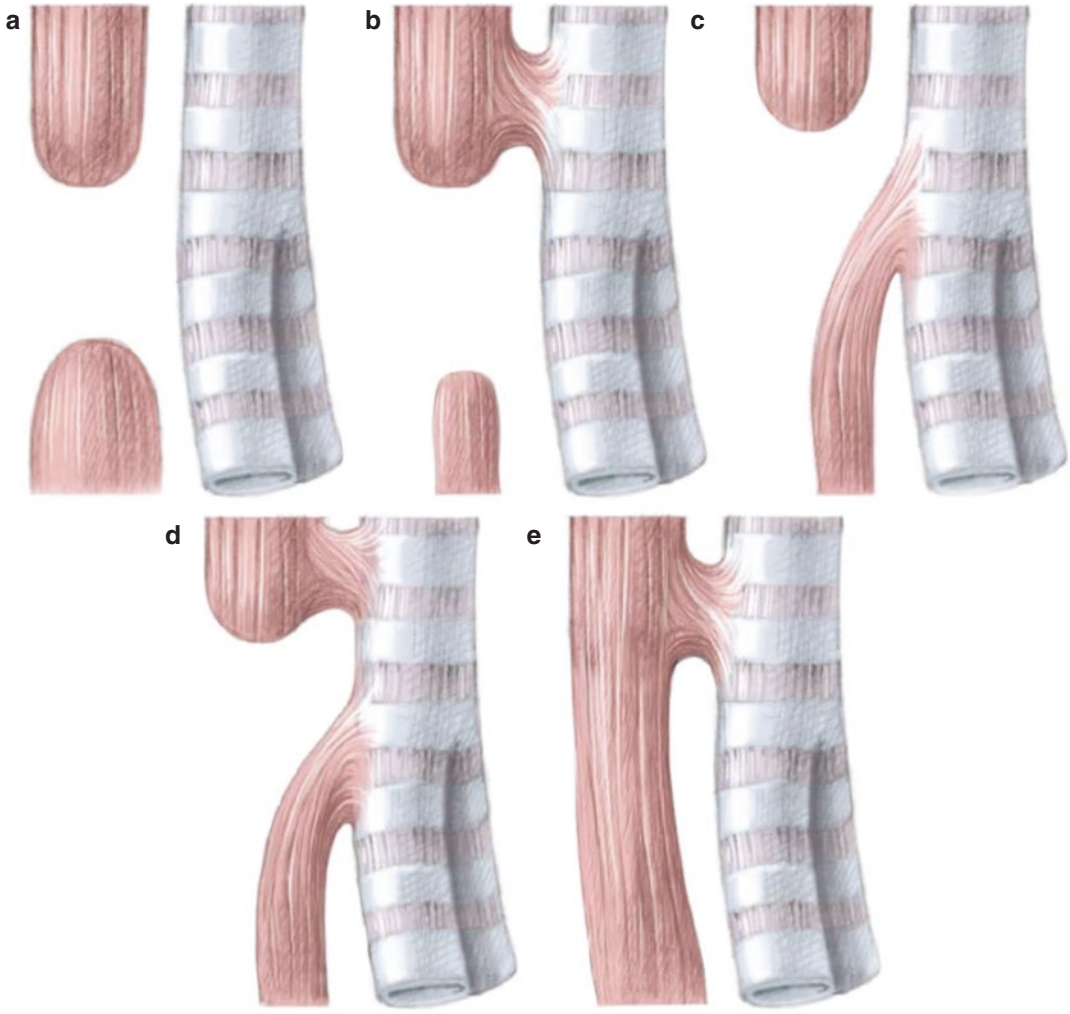

Fig. 17.1 Classification of Esophageal atresia according to Gross classification (Modified from Puri M, Höllwarth ME. Pediatric Surgery. Springer Eds, 2006)

- Cardiovascular anomalies (35%): The presence of the right aortic arch in association with AE is found abnormalities in 2.5–5% of cases. If present, left thoracotomy or thoracoscopy can be preferred is indicated to correct the AE. The persistence of 5% left VCS is observed in the 10% of cases; it can lead to complications such as sinus thrombosis of coronary artery and arrhythmias
- Musculoskeletal anomalies (18%)
- Gastrointestinal tract abnormalities (16%) such as duodenal and ileal atresia, omphalocele, intestinal malrotation, Meckel's diverticulum, heterotopic pancreas, hypertrophic pyloric stenosis
- Genitourinary anomalies (20%) such as cryptorchidism, DSD, hypospadias
- Laryngotracheal anomalies (50%) such as CV paralysis, laryngotracheal cleft, tracheomalacia
- Neurological anomalies such as myelomeningocele, hydrocephalus, occult spinal dysraphism, holoprosencephaly
- Pulmonary anomalies such as pulmonary/lobar agenesis, diaphragmatic hernia

17.3 Diagnosis

Antenatal diagnosis occurs in 10–40% of cases or, frequently, in the first 24 h of life (the prenatal diagnostic process is well described in Chap. 4 of this book). The combination of ultrasound (US) scan and second-line examinations (e.g. magnetic resonance imaging) have improved antenatal diagnosis of EA. Esophageal atresia without TEF can be identified prenatally on the US scan by a small or absent stomach "bubble" and the presence of polyhydramnios from the 14th and 24th week of gestation, respectively. However, these findings are nonspecific and are described in association with many other anomalies [23, 24]. From the third trimester of gestational age, a dilated blind-ending esophageal pouch may be identified as an echoic area in the midline of the fetal neck, but its diagnostic value is still debated [25]. In EA with a distal TEF, detection rates are even lower because of the passage of amniotic fluid into the stomach through the TEF [24–26]. Magnetic resonance imaging (MRI) could be useful to support the ultrasonographic suspicion of EA and to detect potential associated defects.

17.3.1 Postnatal Signs

- Oral bubbly salivation
- Respiratory problems and distress during the first feeding attempt
- A nasogastric tube cannot be passed into the esophagus beyond 10–12 cm

17.3.2 Definition of Surgical Timing

The purpose of the preoperative treatment is the optimization of the general state of the newborn so that corrective surgical treatment can be performed in the best possible conditions. [12, 21, 22]

After the delivery, in intensive care unit are performed:

- complete physical examination to identify associated anomalies
- respiratory assistance
- nutritional support
- antibiotic therapy
- central and peripheral venous line
- arterial access for invasive hemodynamic monitoring
- standard monitoring
- standard blood chemistry tests (CBC, coagulation, intact, EGA if indicated)
- metabolic screening (pre-op by reporting on the card the hours of life at execution
- 36–48 h of life indicating if transfusion occurred)
- Chest and abdomen X-ray are performed separately in two projections to evaluate:
  - proximal stump with the nasogastric tube inside (usually at the level of D2-D4) (Fig. 17.2)
  - presence of air in the stomach in case of FTE (type C or type D)
  - signs of intestinal atresia
  - rib or vertebral anomalies

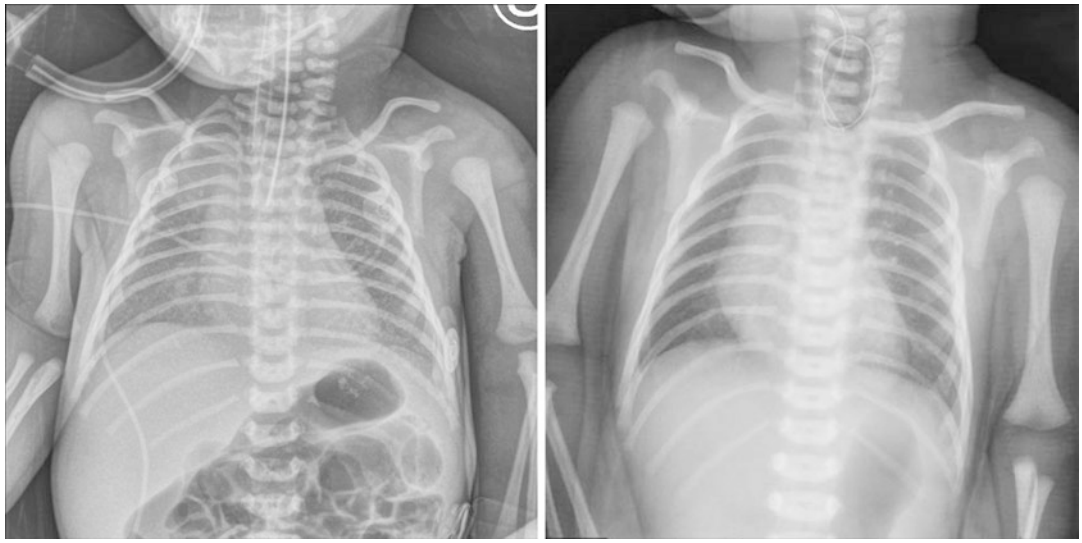

Fig. 17.2 Preoperative X-ray, in both images, the tube does not reach the stomach (on the right the tube forms loops in the proximal esophageal stump)

- Ultrasound of the heart with an electrocardiogram
- Ultrasound of the abdomen
- Ultrasound of the brain and the spinal cord
- Replogle probe positioning in the proximal stump, applying continuous suction to the minimum (80–100 mmHg)

A laryngotracheo bronchoscopy is mandatory before surgery in order to localize the TEF and assess tracheomalacia. The assessment of possible comorbidities is also required before surgery. The differential diagnosis includes laryngotracheoesophageal cleft (midline defect between the posterior larynx and trachea and the anterior wall of the esophagus), esophageal webs/rings (circumferential partial obstruction of the esophageal lumen caused by membranous or diaphragmatic tissue that can be associated with TEF), esophageal stricture (a narrowing of the esophageal lumen caused by a variety of intrinsic and extrinsic disease processes), esophageal diverticulum (a pouch arising from the esophagus), tubular esophageal duplication (a tubular channel that lies parallel to the esophagus and often connects to the main esophageal lumen of the stomach), congenital short esophagus (an abnormally short esophagus accompanied by an intrathoracic location of part of the stomach), and tracheal atresia [27].

17.4 Treatment

The treatment of EA is surgical, and the goal is to create an anastomosis between the proximal and the distal esophageal pouches and, if present, ligate and divide the TEF.

To properly assess the gap length between the two pouches, combined tracheoscopy and fluoroscopy can be performed before the surgery. The surgical approach is dependent on the type of EA and the expertise of the surgeon.

17.4.1 Thoracoscopic Approach

Patient in semi-prone left lateral decubitus (Fig. 17.3), operator in front of the patient, CO_2 insufflation at 4–6 mmHg with close monitoring by the anesthesiologist for possible conversion to thoracotomy if the patient became unstable or if the procedure takes too long; the lung is tractioned and then the longitudinal parietal pleura is opened at the level of the azygos vein (sometimes the azygos vein is sectioned), then the anterior

Fig. 17.3 Semi-prone left lateral decubitus

Vagus and TEF are detected and isolated, the TEF is ligated with nonabsorbable sutures at the level of the pars membranacea of the trachea, and then sectioned.

The proximal esophageal stump is isolated and mobilized (thanks to the movements of the esophageal probe). In this phase, the gap between the esophageal stumps and the feasibility of the anastomosis are reevaluated directly.

The end of the proximal esophageal stump is now opened, and an end-to-end anastomosis between the proximal and distal esophagus is fashioned using interrupted full-thickness fine sutures (Fig. 17.4).

17.4.2 Thoracotomic Approach

Open thoracotomy via an extrapleural approach in order to protect the pleura in the case of an anastomotic leak is still preferred by the majority of surgeons [28]. Technically, the infant is placed on the left side for a right posterolateral thoracotomy. A curved incision 1 cm below the inferior angle of the scapula approximately 5–6 cm long is made. It is crucial to preserve the long thoracic nerve supply to the serratus anterior entering the thorax. The thorax is opened through the fourth or fifth intercostal space. The azygos vein is encountered on entering the mediastinum which is gently mobilized and divided between ligatures to expose the distal esophagus stump. The distal esophagus stump is mobilized circumferentially just distal to the entry of the TEF into the trachea, and a marking seromuscular suture is placed in the lateral wall to assist with orientation. The distal esophagus stump is dissected to the level of the fistula, and the upper and lower extent of the fistula is marked with fine nonabsorbable sutures before dividing the esophagus just distal to the fistula. The tracheal side of the fistula is then sutured with nonabsorbable sutures. The proximal blind esophageal stump is so mobilized sufficiently to produce a tension-free anastomosis. The end of the proximal esophageal stump is now opened, and an end-to-end anastomosis between the proximal and distal esophagus is fashioned using interrupted full-thickness fine sutures.

In long-gap EA, various surgical procedures have been described including delayed primary anastomosis [29, 30] with or without previous esophageal elongation procedures, such as the Foker [31] or Kimura [32] technique, organ interposition using jejunum [33] or colon [34], and gastric pull-up [35, 36]. Anyway, a gold standard in the surgical treatment of long-gap EA is still lacking.

Anyhow, patients born with type A defect should be suspected as having a long gap [1, 12]. To avoid damage to the proximal esophageal stump, esophagostomy should be discouraged in these cases. In addition, if major surgery is impossible, like in type A, gastrostomy is necessary to feed the neonate and may afford more time for preparation for surgery. If mechanical ventilation is needed, air could escape through a distal TEF into the stomach, resulting in

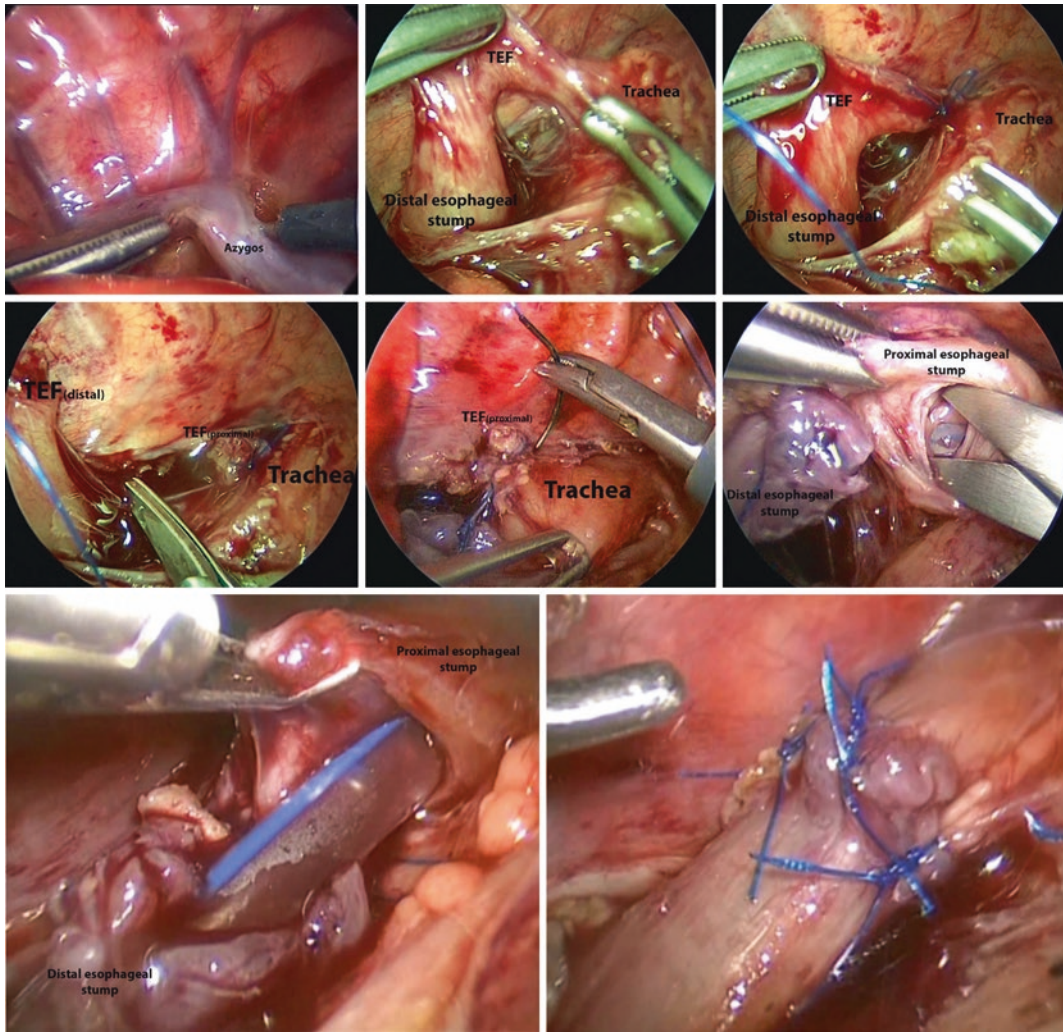

Fig. 17.4 Photo sequence of the thoracoscopic procedure: identification of the Azygos vein, dissection, ligation, and then section of the tracheoesophageal fistula, opening of the proximal esophageal stump, and passage of the tube and in the end the anastomosis

diaphragm elevation or gastric perforation. Thus, the tip of the endotracheal tube must be placed distal to the fistula, and low-pressure ventilation is recommended [26, 37].

Although surgical repair of EA is preferably scheduled after preoperative management and assessment of potential comorbidities, this is not possible in patients with respiratory distress in who immediate trans pleural ligation of TEF is required to ameliorate respiratory status [1, 12].

17.4.3 Postoperative Management

- Invasive respiratory support for a period of at least 48 h.
- Close monitoring of the position of the transanastomotic tube (Fig. 17.5) and thoracic drainage.
- Between the fifth and seventh postoperative day, an esophagogram is performed (Fig. 17.6), if absence of dehiscence or leakage, gradual

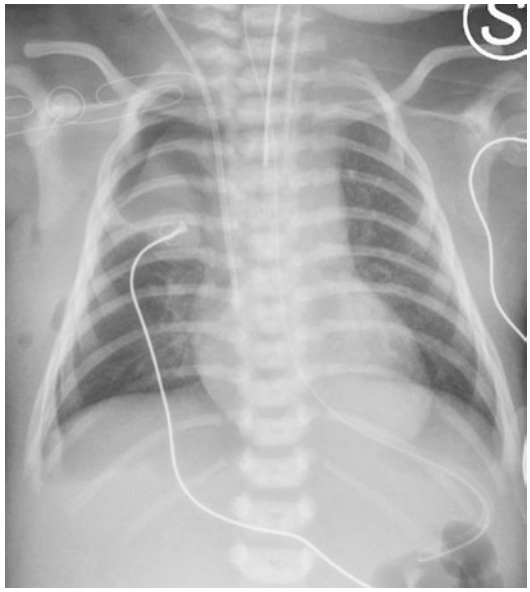

Fig. 17.5 The esophagogram, after the surgical procedure, shows the correct position of the nasogastric tube that passes through the anastomosis

resumption of feeding per Os (trans-anastomotic tube and thoracic drainage will be removed later after indications of the surgeon).

17.5 Complications

Postoperative complications after EA repair include anastomotic leakage or stricture, recurrent TEF, gastroesophageal reflux, dysphagia with growth failure, respiratory complications, tracheobroncomalacia, and neurocognitive disorders [1, 28, 38].

Anastomotic leakage occurs in up to 20% of babies born with EA and can generally be treated conservatively, however, with the risk of evolving into cicatricial stenosis. Traditionally, a postoperative chest tube and/or trans anastomotic nasogastric tube would be left in situ, but the latest

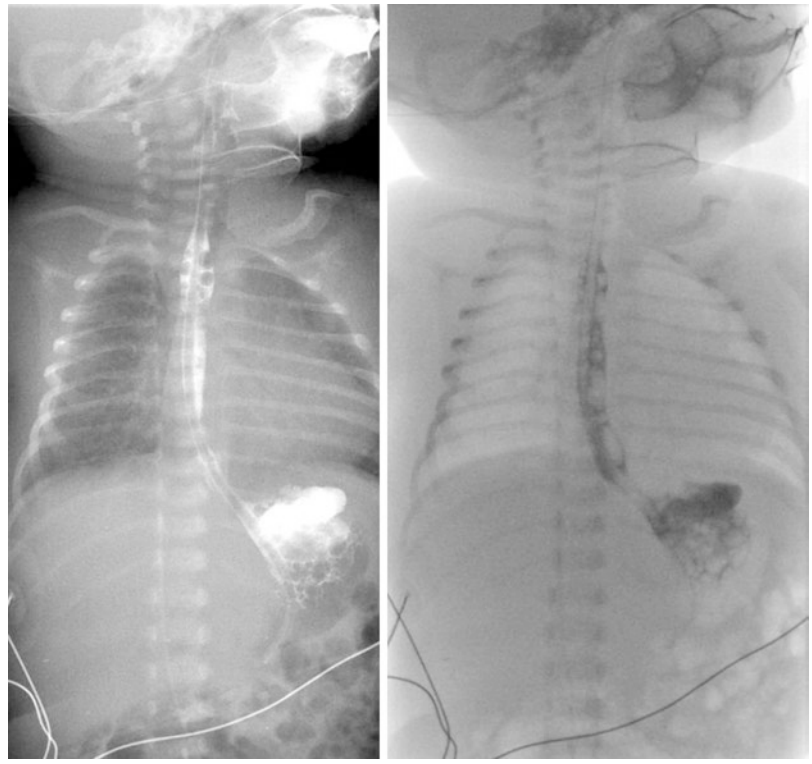

Fig. 17.6 The esophagogram shows the passage of contrast without any leakage or sign of stricture

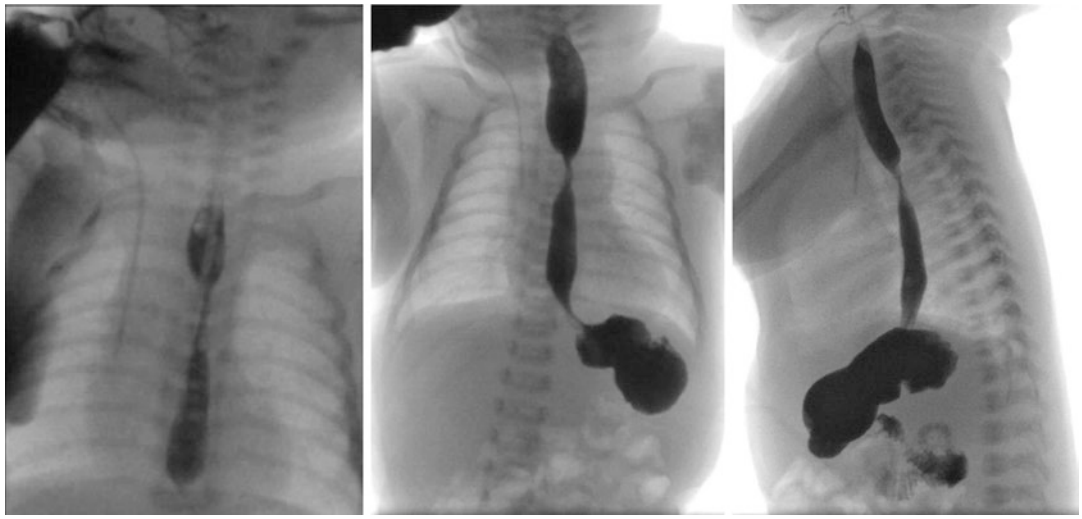

Fig. 17.7 The esophagogram shows the anastomotic stricture; in the first picture the nasogastric tube is still in place, and in the other two the nasogastric tube has been removed

published studies reported that both of them do not decrease complication risk [1, 38, 39].

Anastomotic stricture (Fig. 17.7) represents a frequent complication that can affect up to 40–60% of patients and occurs in the majority of cases in the first year of life. Diagnosis can be made clinically (dysphagia, entrapment of food bolus, and aspiration pneumonia) or instrumentally (esophagogram and endoscopy). Esophageal dilation is the nonoperative treatment of choice for anastomotic strictures, and it can be performed by balloon dilation or bougienage dilation [40]. Incidence of *recurrent TEF* range between 3% and 10%, and risk factors include anastomotic tension or leak and TEF ligation instead of division. Typically, the presence of this complication is associated with cough, dyspnea and cyanosis with meals, and recurrent lung infections. Instrumental clinical diagnosis is often difficult (esophagogram, EGDS, tracheoscopy) and can also occur remotely.

Treatment strategies described for recurrent TEF are endoscopic injection of glue or trichloroacetic acid and corrective surgery [15–41].

Gastroesophageal reflux represents the most common complication, especially in the first 2 years of life, and can lead to feeding problems, vomiting, growth failure, and recurrent respiratory tract infections. Reflux is favored by traction on the lower esophageal stump that must be performed in order to perform the anastomosis with alteration of the esophagus–gastric junction and reduction of the tone of the lower esophageal sphincter.

In addition, the propulsive peristalsis in the lower segment of the esophagus is missing, and the clearance time of the acidic material is significantly longer than the normal clearance so that chronic exposure to acid reflux causes esophagitis of various degrees. The 24 h pH impedance measurement, always to be carried out after the suspension of the PPI, represents the gold standard for diagnosis of the disease (GER), for the identification of both acid and non-acid reflux.

Endoscopy with biopsies allows to highlight erosive microscopic esophagitis but also to evaluate the possible association of eosinophilic esophagitis. Esophagogastroduodenal gram is necessary to exclude malrotation or other structural anomalies that can often be associated with esophageal atresia (congenital stenosis of the distal esophagus, duodenal anomalies).

ESPGHAN-NASPGHAN guidelines recommend treating these patients with pump inhibitors (PPIs) during the first year of life and to continue only if symptoms persist.

Although medical therapy with PPIs is preventively and widely used, a percentage of these

patients undergo surgical treatment to prevent reflux [42–45].

Respiratory complications such as dyspnea, bronchospasm, recurrent episodes of bronchitis, daily cough, and episodes of recurrent and prolonged pneumonia are common in patients with AE from the early months of life but become less frequent with time.

Respiratory symptoms can be secondary to aspiration (alteration of esophageal motility and/or esophageal stenosis), recurrent TEF, GER, tracheomalacia, and alteration of the motility of the vocal cords.

According to some recent works, in a significant percentage of patients studied in the long run, there is an alteration of lung function (in particular restrictive alteration) or pulmonary damage (bronchiectasis, atelectasis) [46–54].

Tracheomalacia (TM) affects 75% of children with AE, and it consists of a localized or generalized weakness of the tracheal wall due to cartilage anomalies that cause the lumen to collapse during expiration or coughing. Clinically, it has a varied spectrum of manifestations: from the typical "barking cough" to recurrent lung infections up to severe apneas. The diagnosis is essentially endoscopic, but the suspicion is based on respiratory disorders.

Alternatively, CT can be useful to rule out other relatively alternating frequent problems, such as tracheal diverticulum, vascular compression, and intrinsic stenosis. It is clinically significant in 10–20% of patients. The prognosis is basically benign since TM tends to 20% improve with the child's growth; however, in the most serious cases with important life-threatening apneas or recurrent pneumonia, the treatment of choice is surgical and can be aortopexies, posterior tracheopexy, or other interventions (stent, exoskeleton, tracheal resections, and tracheotomy). The effectiveness of the intervention of aortopexy is reported in 35–88% of cases.

Spirometry allows you to identify changes in lung function and indicate more detailed assessments. Airway endoscopy (flexible or rigid) allows the evaluation of laryngeal cleft, subglottic stenosis, tracheomalacia, mucosal alterations from GER, and the identification of inflammatory cells (aspiration) or pathogens responsible for recurrent pneumonia. Chest CT is indicated in cases of chronic respiratory symptoms, recurrent infections, and allows to diagnose bronchiectasis, pneumonia, and atelectasis [1–4, 7, 53, 55].

17.6 Esophageal Duplication

17.6.1 Introduction

Esophageal duplication (ED) is a product of abnormal foregut embryogenesis and may be part of a spectrum of disease that includes esophageal atresia as well as congenital bronchopulmonary anomalies [30, 31, 56, 57]. Gastrointestinal duplication occurs in 1/4500 live births with nearly 20% of these malformations representing esophageal duplications [31, 32, 57, 58]. ED seems to occur in equal frequency among male and female babies and is associated with other abdominal duplications in up to 25% of cases [32, 33, 58, 59].

17.7 Classification

ED has three different morphologic variants that are cystic, tubular, and diverticular. All these three morphologies have typical characteristics that are a well-developed coat of smooth muscle, an epithelial lining representing some portion of the alimentary tract, and a connection with the esophagus [33, 34, 59, 60].

ED can usually be observed in the lower esophagus and is positioned in the posterior mediastinum with projection into the thorax [35, 61]. Histologically, the respiratory epithelium is commonly encountered and ectopic gastric mucosa is reported in up to 50% of esophageal duplications. Notably, the majority of these lesions are benign [33, 36, 59, 62].

17.8 Diagnosis

Symptoms of ED habitually appear before 2 years of age and depend on the anatomic position of the lesion, the mass effect, secondary

complications to luminal secretions or infection [36, 38, 62, 63]. The most common symptoms are secondary to mass effect on airways, even if the majority of these lesions are found incidentally [34, 39, 40, 60, 64, 65]. A less common presenting symptom is gastrointestinal hemorrhage secondary to the atopic gastric mucosa [41, 66].

Diagnosis of the duplication cyst is usually made by chest X-ray, but the further characterization of the mass is usually accomplished with a computed tomography scan of the chest. An abdomen ultrasound scan should be performed as well for eventually associated duplications [35, 61]. Characteristically, these lesions are spherical, approximately 2–10 cm in size with a hyperechoic inner mucosal layer, and a hypoechoic outer muscular layer. Peristalsis is a very specific finding [42, 43, 67, 68]. Additionally, an esophagogram followed by endoscopy can add information about the relationship of a communicating duplication to the esophageal hiatus and gastroesophageal Junction [44, 45, 69, 70]. Prenatal diagnosis of esophageal duplication has also been described in the literature as a cause of fetal non-immune hydrops secondary to compression of the vena cava [35, 46, 61, 71].

17.9 Treatment

Surgical excision of ED is recommended because of the reported risk of cyst infection, bleeding, erosion, perforation, and the risk for malignant transformation [30, 47, 56, 72].

The operative approach is primarily dictated by the location of the lesion. Cervical duplications are best excised via cervical incision, but minimally invasive resection is mandatory for thoracoabdominal lesions if feasible [34, 38, 48, 60, 64, 73]. Technically, to treat these malformations, a thoracoscopic approach or a muscle-sparing posterolateral thoracotomy at the level of the fourth or fifth intercostal space are used. Once duplication is identified, it must be gently dissected off the surrounding structures. The cyst must be entirely dissected, and the content aspirated, and if present, an open communication between the duplication and the originating organ must be identified and repaired with interrupted stitches. In order to reduce recurrence rates, complete excision of these lesions is more efficient than marsupialization [30, 48, 56, 73].

17.10 Conclusion

International literature regarding ED is scant for analyzing outcomes after surgical resection. However, a high success rate is reported in two series of duplication completely excised at a single stage [38, 49, 64, 74]. Finally, associated malformations and spinal/vertebral anomalies seem to contribute the most to long-term morbidity [34, 35, 60, 61].

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Congenital Diaphragmatic Hernia

18

Girolamo Mattioli and Federico Palo

18.1 Introduction

Congenital diaphragmatic hernia (CDH) is a birth defect of the diaphragm that occurs in about 1–5/10,000 live births. Particularly, it leads to a lack of separation of the abdominal and thoracic cavities secondary to a failure in the fusion of the pleuroperitoneal folds. The development of the diaphragm is completed around the seventh week of intrauterine life, thanks to the fusion of the transverse septum with the meso-esophagus and pleuro-peritoneal folds. If the separation between the thorax and the abdomen is not complete when the primitive intestine migrates from the yolk sac to the abdominal cavity (9th to 10th week of gestation), the abdominal viscera can herniate in the thorax through the two pleuro-peritoneal channels (right and left). Since the primary intestine rotates counterclockwise inside the abdominal cavity, the diaphragmatic hernia appears more frequently to the left (85%), more rarely to be right (10%), or bilateral (5%). The movement of abdominal contents in the thoracic space results in pulmonary hypoplasia and, consequently, this abnormal development leads to increased pulmonary vascular resistance and significant pulmonary hypertension [1, 2]. Management of the postnatal pulmonary hypertension in newborns with CDH is the key issue for the survival of these children.

18.2 Classification

Two major types of CDH have been described in neonates. The Bochdalek-type CDH (80–90%) is a defect in the posterolateral portion of the diaphragm with herniation of the stomach, intestines, liver, and/or spleen into the chest cavity. About 85% of Bochdalek's hernia occurs on the left side, 10% on the right, and 5% are bilateral. Morgagni's hernia is a defect in anteromedial portion of the diaphragm, and it is very rare (2%). Para-esophageal hernia occurs in 15–20% of the cases. Notably, defect size is known as an important risk factor from 2006. Originally, defects were coded from A to D. "A" refers to a defect surrounded by muscle, "B" and "C" to defects from mild to severe of a portion of diaphragm tissue, and "D" defects to a complete (agenesis) or near-complete absence of the diaphragm.

CDH can present as either an isolated or a complex anomaly. Isolated CDH is observed in about 50–60% of probands, while complex forms are observed in 40–50% of probands associated with other congenital anomalies [3–5].

Main anomalies associated with CDH:

G. Mattioli (✉) · F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini, University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_18

- intestinal malrotation
- skeletal malformations (limb, rib, or vertebral anomalies)
- cardiac anomalies (25%, e.g., perimembranous DIV, aortic arch hypoplasia, aortic coarctation, Fallot tetralogy, transposition of fatty vessels)
- airway abnormalities (tracheal stenosis, tracheal bronchus, and tracheal malformations)
- neural tube defects
- defects of the abdominal wall
- craniofacial malformations
- urinary tract abnormalities
- alteration of enteric innervation (esophagus-gastric hypomotility)

Morgagni hernia is a rare (2%) anterior retrosternal or parasternal hernia caused by a defect in the development of the sternal fixation and often incidentally discovered in older children. Additionally, it is generally accompanied by a hernia sac [3].

18.3 Diagnosis

Approximately two-thirds of fetuses with CDH are now diagnosed prenatally (the prenatal diagnostic process is well described in Chap. 4 of this book). The most common left-sided defect of CDH is often detected by ultrasound (US) scan. Magnetic resonance imaging (MRI) and fetal echocardiography are usually performed after the detection of a potential diaphragm defect on a US scan [1, 6].

Different prognostic predictors have been suggested in CDH. Herniation of the liver into the chest is known to be a poor prognostic factor.

In fact, this often suggests a large structural defect in the diaphragm with a more impact on the thoracic organs and worse pulmonary hypoplasia and pulmonary hypertension. Moreover, liver herniation is extremely predictive of the need for extracorporeal membrane oxygenation (ECMO) and increased mortality [7]. Observed-to-expected lung–head ratio (O/E LHR) is actually one of the standard prenatal metrics to help predict morbidity and mortality. O/E LHR is the ratio of the right lung area to the head circumference, corrected for the rapid growth in lung development during the third trimester of pregnancy [2, 8].

Awaiting delivery, the expectant remedy for selected CDH babies has become fetal intervention. The fetoscopy endoluminal tracheal occlusion (FETO) is based on the positioning of a balloon into the fetal trachea causing an obstruction. In particular, this obstruction stops fluid from exiting the lungs, leading to increased pulmonary pressure and lung size [1, 9]. (this procedure is discussed in detail in Chap. 4).

Nevertheless, further studies are needed to help answer important questions about this procedure.

18.4 Treatment

18.4.1 Definition of Surgical Timing

Although historically CDH was considered a surgical emergency, it is now worldwide accepted that CDH is a physiologic emergency, and its initial management should be aimed at controlling pulmonary hypertension [1, 2, 10].

After the delivery, in intensive care unit are performed:

- Monitoring (pre- and post-ductal O_2 saturation, blood pressure monitoring)
- Blood gas analysis
- Chest X-ray (exclusion of PNX, confirmation of the diagnosis through the position of the nasogastric tube) (Fig. 18.1)
- Ultrasound of the heart, brain, and the abdomen.

The goal in the primary management of newborns with CDH is to provide oxygenation and ventilation without causing pulmonary vasospasm crisis or additional damage to the underdeveloped lung. Thus, gentle lung ventilation and permissive hypercapnia (PaCO2 of 40 to 60 mmHg) are the norms for these children [11], with pre-ductal O_2 saturation between 85% and 95 and post-ductal saturation >70%. Adequate blood pressure is also

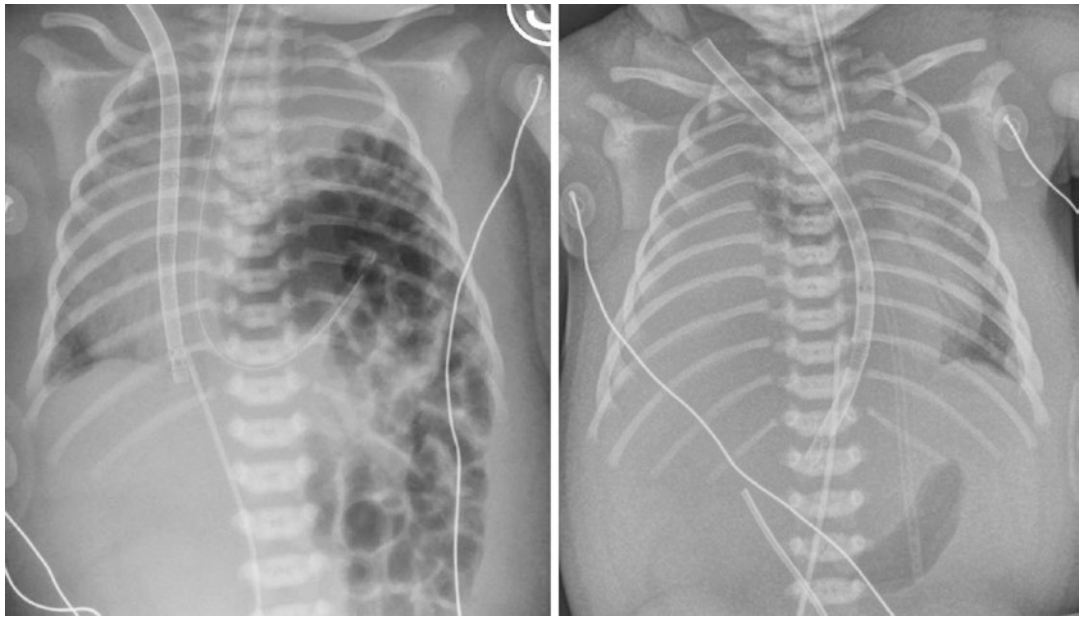

Fig. 18.1 On the left the X-ray of a left diaphragmatic hernia (the position of the nasogastric tube confirms the diagnosis). On the right, instead, the X-ray of a right diaphragmatic hernia. Both patients were in ECMO for a bad clinical condition

important to avoid severe pulmonary hypertension that can lead to right heart failure in smaller children (pH >7.20, lactates <12 mg/dL, diuresis >1 mL/kg/h). Treatment of right heart failure is based on inotropic support (e.g., dopamine) and reduction of right heart afterload decreasing pulmonary bed resistance (using inhaled nitric oxide and/or milrinone) [2, 12, 13].

ECMO (Fig. 18.2) is required for rescue support in CDH neonates with severe pulmonary hypertension. Giving the lack of specific criteria for ECMO, it is widely accepted that preductal oxygen saturations less than 85%, peak inspiratory pressures greater than 25 cm H_2O, hypotension resistance to therapy, and inadequate perfusion based on urine output or increasing lactate are signs of the need for it. The typical indication for ECMO is a constant oxygen index of greater than 35–40. [1, 14]

Bleeding is the main determinant of mortality; for this reason, a protocol of prevention and treatment of bleeding is essential if the patient is operated on in ECMO:

- PLT >100 × 103
- Fibrinogen >100 mg/dL
- ACT 160 s with the increase in flows to at least 100–150 mL/kg
- Administration of tranexamic acid (bolus 4 mg/kg, then 1 mg/kg/h for 24 h)
- In case of massive bleeding, administer activated factor VII at a dose of 90 mcg/kg repeatable every 2 h until bleeding stops, then, if necessary, 90 mcg/kg every 6 h.

18.4.2 Surgical Treatment

Surgical repair of the diaphragm is an emergency only if there are signs of bowel ischemia caused by the hernia. The operation can be performed in the operating room if the infant is stable, but it is almost always preferable to undertake surgery in the neonatal intensive care unit. The goal of surgery is to obtain a tension-free repair of the defect, with a patch if necessary (made by permanent, biosynthetic, or composite material).

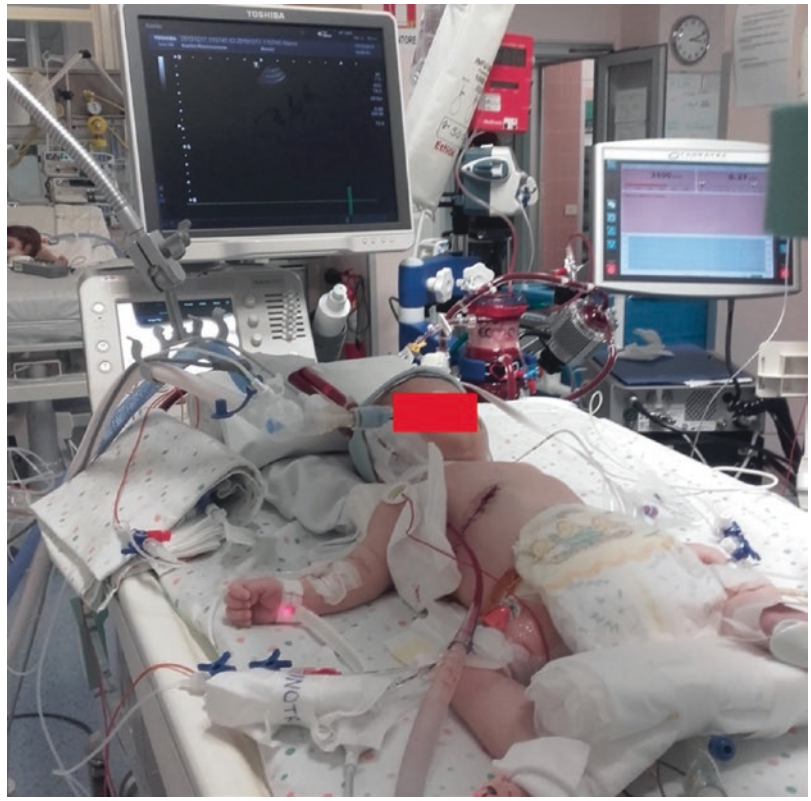

Fig. 18.2 Patient with right CDH in ECMO

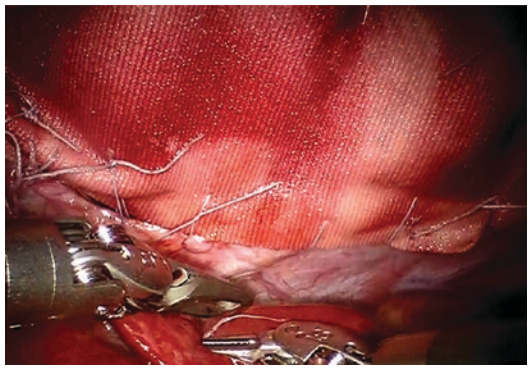

Fig. 18.3 Repair of the diaphragmatic defect with a patch during a robotic procedure

Polytetrafluoroethylene (PTFE) is the material most commonly used by expert surgeons [15] (Fig. 18.3).

Specifically, the patient is positioned in a supine position with a small roll placed across the back at the level of the diaphragm. The surgical incision can be subcostal or median laparotomy, many surgeons prefer the first which allows excellent exposure of the diaphragmatic defect. The peritoneum is entered, and with gentle traction herniated viscera are reduced into the abdomen. The edges of the defect are then carefully inspected. Repair of the defect, with or without a patch, is performed with interrupted simple absorbable or unabsorbable sutures. If the intestine is malrotated, a Ladd procedure should be performed. A tension-free fascial closure is sometimes difficult to achieve and occasionally requires the use of a temporary silo, in order to avoid respiratory problems or a possible abdominal compartment syndrome (Fig. 18.4).

The placement of thoracic drainage is optional. If positioned, the drainage is kept clamped to avoid the creation of a negative pressure that could cause hypoplastic lung overdistension. The presence of liquid in the thoracic cavity makes its expansion more gradual. Sometimes the drainage is placed without suction in the early postoperative phases (Fig. 18.5).

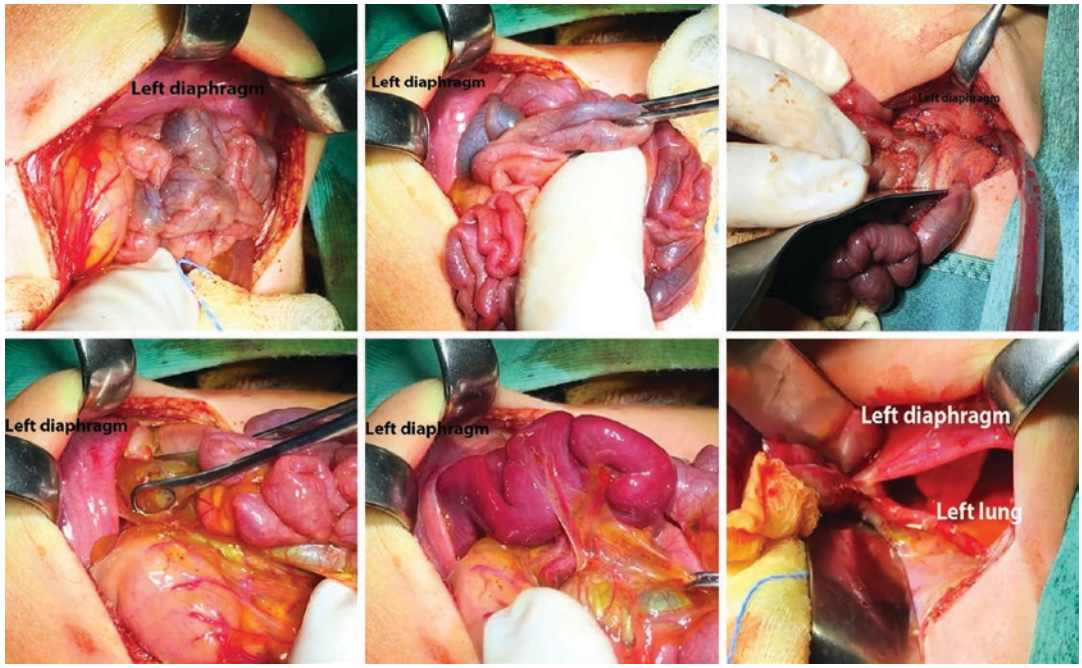

Fig. 18.4 In this photo sequence, an open surgical repair of left diaphragmatic hernia

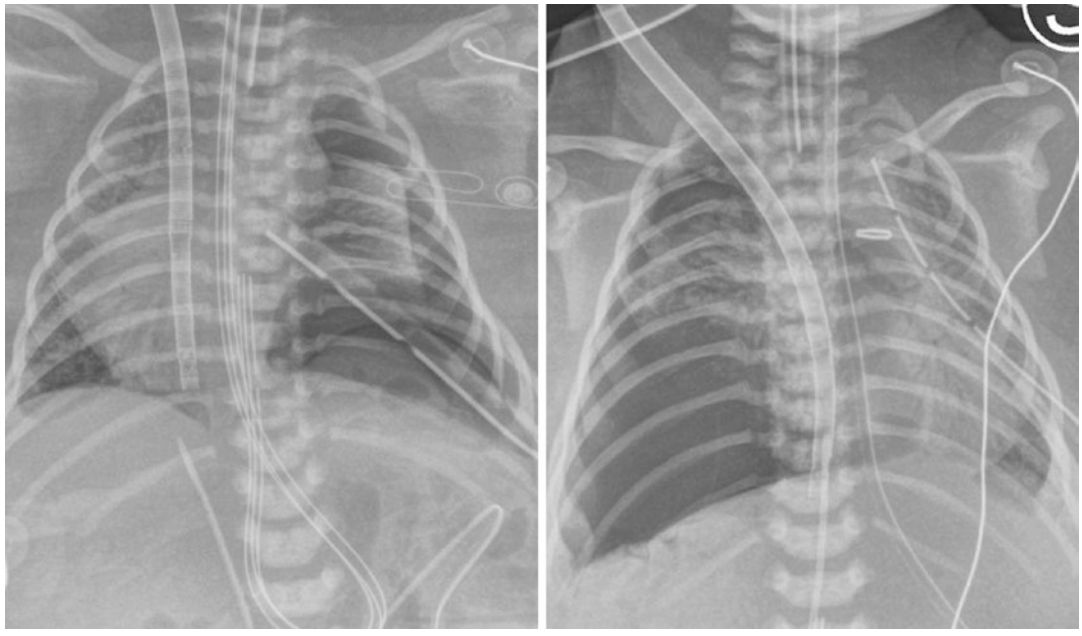

Fig. 18.5 On the left the X-ray after surgical correction of the defect with a chest tube in place. On the right, the X-ray after surgical correction of right diaphragmatic hernia, the chest tube has not been positioned. The patient had a left thoracic fluid collection before the surgical procedure, and for this reason, a left chest tube has been positioned. The clips are the result of the ligation of the Botello arterial duct

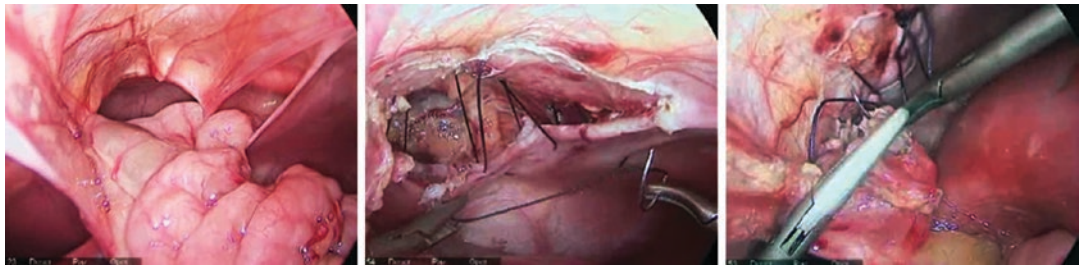

Fig. 18.6 Laparoscopic procedure for left diaphragmatic hernia

Although minimal invasive repair of the diaphragmatic hernias (laparoscopic or thoracoscopic approach) (Fig. 18.6) has been adopted in many centers, some studies suggest that there is an increased risk of recurrence with the thoracoscopic approach [16].

18.5 Conclusion

The survival rate in neonates with isolated CDH is about 70–90%. Gentle lung ventilation, permissive hypercapnia, and standardized treatment protocols seem to have increased the overall survival rate over the last few decades [2, 16].

Neonates with CDH are more inclined to a variety of long-term problems:

- *Impairment of lung function:* In the first years of life, bronchopulmonary dysplasia (BPD, 33–52% at discharge), bronchospasm, pulmonary hypertension (30% of patients at 2 months of age), pulmonary hypoplasia, inhalation pneumonia. In all, 50% of children with diaphragmatic hernia remain oxygen dependent at 28 days of age, while 16% remain oxygen dependent at discharge for an average of 14.5 months (2% up to the age of 2 years). The use of bronchodilators is necessary in 30% of patients at 2 months, and many require inhaled steroid therapy. In all, 7% of people have pneumonia in the first year of life. Broncho-pneumonic episodes and bronchospasm can be prevented by stopping oral feeding in the case of pharyngo-oesophageal incoordination and through timely recognition and treatment of reflux pathology. Anti-pneumococcal and anti-flu vaccination is recommended; Palivizumab prophylaxis should be performed in all children with CDH and BPD. 50% of surviving adult patients have impaired respiratory function tests [17].
- *Gastroesophageal reflux and impaired gastric motility* are found in 40–90% of children with CDH, abnormal anatomy of the gastro-oesophageal hiatus, absence of His angle, and herniation of the stomach in the chest are some of the mechanisms involved in the high incidence of reflux. Dilatation and ectasia of the esophagus have been described in patients with CDH; these subjects have reflux in 70% of cases. The incidence of gastroesophageal reflux correlates with the size of the diaphragmatic defect and the need to use prosthetic patches. Lung morbidity can be aggravated by inhalation associated with gastroesophageal reflux. Frequent finding of esophagitis in adult survivors indicates the need for long-term surveillance.

  A high degree of suspicion for reflux disease should be maintained in all patients with CDH. Anti-reflux surgery represents a therapeutic option in patients in whom medical therapy fails [17].
- *Growth failure:* Over 50% of CDH patients, by the first year of life, weigh less than the 25th percentile, while at 2 years of age, the percentage weighing less than 5th percentile is greater than 40%. Inability to oral nutrition, oral aversion, gastroesophageal reflux, and impaired motility of the first tract of the digestive system are the main causes of poor growth in subjects with CDH. About 33% of children with CDH need to be discharged with a gastric

tube or gastrostomy to obtain an adequate nutritional intake. The use of a nose or oro-gastric tube can compromise oral nutrition (oral aversion), with the need for prolonged rehabilitation.

In this sense, the transition to gastrostomy must be considered early when the removal of the gastric tube is not conceivable within a few months and promote oral nutrition through sucking stimulation [17].

- *Neurocognitive delay and behavioral disorder:* CDH patients frequently experience delayed psychomotor development (approximately 33% of survivors). The incidence of neurological disorders correlates with the size of the defect and with the need for recourse to ECMO (67% ECMO vs 24% non-ECMO) [17].

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Diaphragmatic Eventration

19

Girolamo Mattioli and Federico Palo

19.1 Introduction

Diaphragmatic eventration (DE) constitutes an atypically elevated elevation of one or both hemidiaphragm secondary to both congenital and acquired issues. In particular, congenital diaphragmatic eventration refers to a developmental defect in the muscular portion of the diaphragm [1]. The reported incidence of congenital DE is 1 per 1,400 children who underwent chest radiographs. Congenital DE is reported more commonly among males and is more likely to affect the left hemidiaphragm [2, 3].

19.2 Classification

DE is due to both congenital and acquired factors. Congenital cases are characterized by a malformation of the diaphragmatic muscle, which occurs embryologically because of abnormal migration of myoblasts. Instead, in acquired cases, DE is caused by phrenic nerve palsy that can occur for several reasons (e.g., trauma or cardiac surgery), and therefore, the amount of diaphragmatic muscle fibers is normal [4–6]. Notably, acquired DE may also develop as a consequence of traction on the phrenic nerve during delivery [7].

19.3 Diagnosis

Clinical manifestations of congenital DE in children are various. The majority of patients are totally asymptomatic but sometimes may present with mild gastrointestinal conditions or life-threatening respiratory distress. The main symptom that patients with DE may experience is dyspnea [8, 9].

Diaphragmatic eventration may easily be missed or misdiagnosed. In general, diagnosis of DE can be achieved incidentally if an elevated hemidiaphragm is noted on a plain chest X-ray [10]. Fluoroscopic evaluation of the diaphragm ("sniff test") can be used to confirm the paradoxical movement of the diaphragm [11] (Fig.19.1).

19.4 Treatment

Surgical treatment for DE is mandatory exclusively for symptomatic children. Small eventrations with slight respiratory symptoms may be treated conservatively and can safely be observed. The gold standard operation for symptomatic patients is plication of the diaphragm via thoracotomy or laparotomy. Recently, both thoracoscopic and laparoscopic plication have been

G. Mattioli (✉) · F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini, University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_19

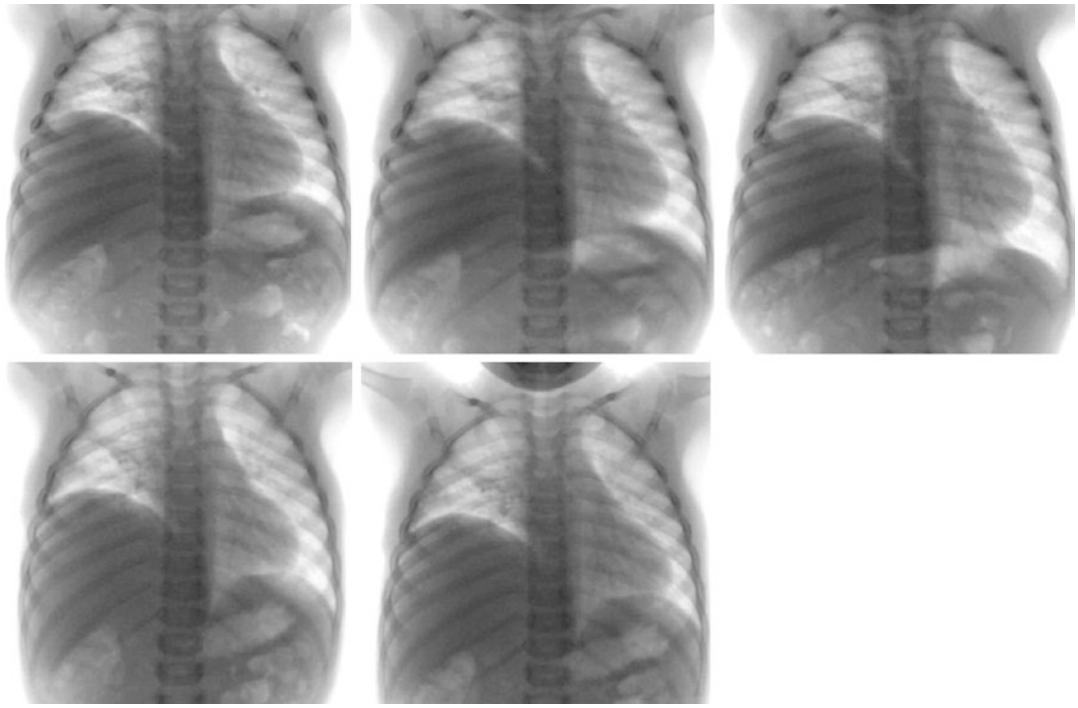

Fig. 19.1 Dynamic radiological study of the chest: the right hemidiaphragm presents paradoxical movements, resulting in more relief than the contralateral

reported for DE in pediatric patients. The thoracoscopic approach is reported to be associated with a large working space and direct visualization of the phrenic nerve that must be preserved, on the other hand, laparoscopic plication is associated with less intercostal nerve pain and a larger working space [12–14].

Unilateral DE is most commonly approached via a seventh intercostal space thoracotomy, which allows for ideal visualization of the phrenic nerve and its branches that must be protected from injury during the operation. The concept of surgery for DE is to excise the thinned portion of the hemidiaphragm (usually centrally located) and approximate the edges with nonabsorbable, interrupted 2–0 sutures without excessive tension. The use of a stapler has also been described in the literature. In case of an acquired eventration, repair involves plication of redundant areas of the diaphragm to create a taut closure by grasping the central portion of the affected hemidiaphragm with a non-crushing clamp. Thus, the plication should be done in an anteromedial to posterolateral configuration with nonabsorbable sutures (Fig. 19.2). Intrapleural drainage is usually maintained for some days following the transthoracic and thoracoscopic approaches [11, 13, 14].

19.5 Conclusion

The most frequent complication reported in children after diaphragm plication is recurrence. Notably, recurrence was observed predominantly in cases treated laparoscopically [15]. In conclusion, if technically feasible, all pediatric patients with DE should undergo plication of the diaphragm using thoracoscopy. However, further studies are needed to make definitive conclusions.

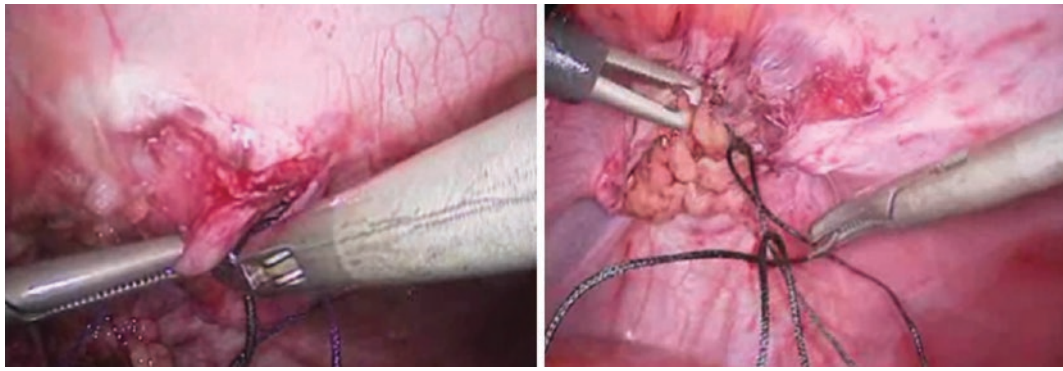

Fig. 19.2 Intraoperative laparoscopic diaphragmatic plication

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Sternal Clefts and Cantrell Syndrome

20

Girolamo Mattioli and Federico Palo

20.1 Introduction

Sternal cleft (SC) is one of the most common congenital defects in the group of anterior chest wall malformations (Fig. 20.1). The reported incidence of SC is about 1 in 50.000–100.000 live births [1]. In particular, pentalogy of Cantrell (PC) is a rare collection of anomalies, including omphalocele, anterior diaphragmatic hernia, sternal cleft, ectopia cordis, and some form of intracardiac abnormality [2]. Historically, it has been hypothesized that PC is due both to an offending event in the development of the septum transversum and to a failure in migration and fusion of primordial sternum during embryonic life. Furthermore, Pentalogy of Cantrell is reported in association with chromosomal abnormalities and its incidence is about 1 in 65.000 to 200.000 live births with a male predominance [3, 4].

20.2 Classification

Sternal malformations were first classified by Shamberger and Welch in four types: thoracic ectopia cordis, cervical ectopia cordis, thoracoabdominal ectopia cordis (pentalogy of Cantrell), and sternal cleft [5]. Successively, SC was further classified into complete or partial respectively superior or inferior (Table 20.1). Notably, superior partial SC is more common and rarely can be associated with PHACES syndrome (posterior fossa malformations, facial hemangiomas, arterial anomalies with coarctation of aorta, cardiac defects, eye abnormalities, sternal cleft, and supraumbilical raphe); instead, PC is reported in association with an inferior partial cleft that is more uncommon [6, 7]. Additionally, multiple cases of PC have been associated with chromosomal abnormalities, such as Trisomy 21, Trisomy 18, or Turner's Syndrome [3].

20.3 Diagnosis

Major sternal clefts, as well as PC, maybe diagnosed using prenatal ultrasound (US) during the second trimester of gestation. Fetal magnetic resonance imaging (MRI) is often performed to confirm the diagnosis, and if PC is suspected, fetal echocardiography is mandatory to detect the presence of intracardiac abnormalities. Moreover, chromosomal analysis is also important in these cases in order to inform and counsel the family.

A visible and palpable pulsatile mass below the skin of the lower chest and upper abdomen on physical examination is generally noted. Anterior abdominal wall defect is observed if present. Children with PC frequently present with dyspnea and cyanosis for the associated heart

G. Mattioli (✉) · F. Palo
Pediatric Surgery, IRCCS Giannina Gaslini, University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_20

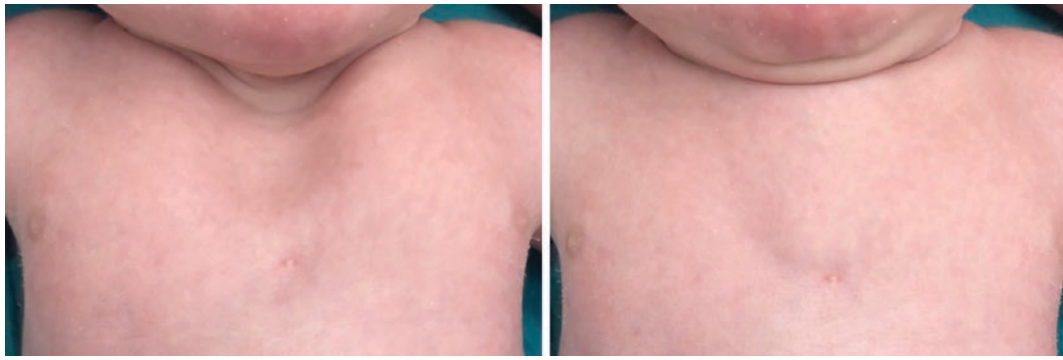
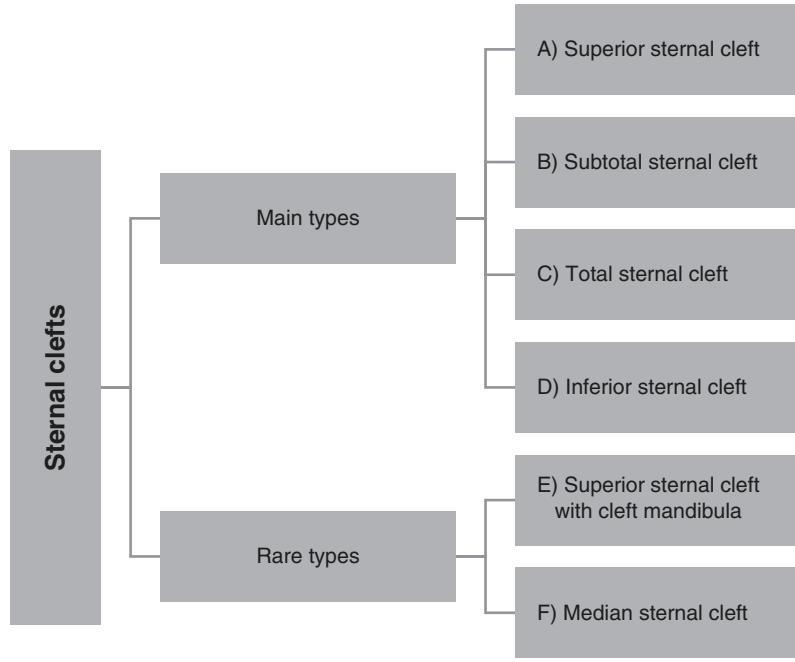


Fig. 20.1 Patient with a sternal cleft, on the left the classic depression during inspiration, on the right, instead, bulging in the expiratory phase

Table 20.1 Sternal clefts classification



anomaly. An echocardiography should be repeated in the postnatal period in order to confirm the presence of intracardiac anomalies and prenatal diagnosis [7]. Thoracoabdominal computed tomography (CT) helps provide additional information [8].

20.4 Treatment

The management of children with PC requires the coordination of a multidisciplinary team involved from the prenatal diagnosis till definitive surgical repair. Stable neonates may benefit from primary conservative management including prophylactic antibiotics and daily dressing of the omphalocele sac. Surgical repair of PC aims at repairing cardiac anomalies, reestablishing anatomy, and fixing the thoracoabdominal wall and diaphragmatic defects [9]. Both multi-stage and single-stage surgical repairs have been described for correcting PC. Multi-stage repair seems to reduce significantly postoperative respiratory insufficiency and mortality. Specifically, intracardiac anomalies should be fixed first and subsequently thoracoabdominal wall defects are

corrected. On the other hand, a single-stage operation is possible in babies without intracardiac anomalies. Notably, immediate neonatal intervention is required in babies with a large upper omphalocele and lower sternal cleft. Initial thoracic skin closure must be achieved to avoid infection. Repair of the abdominal wall defect is of secondary importance and may require the use of Teflon mesh or other prosthetic material [10–13].

Several options for the repair of SC are available. To repair a sternal cleft in neonatal age, a midline incision is performed; if the sternal cleft is partial, a V-shaped incision is performed where the normally fused sternum begins, in order to facilitate the primary closure. The sternal halves are tight together with some unabsorbable stitches.

When performing a primary repair of the sternum, it is important to be sure that the closure is not causing any hemodynamic troubles by diminishing the venous return, due to the dramatic increase in the mediastinal pressure. To reduce this risk, Torre et al. advise to remove completely or partially the thymus [14].

If the compression is too much or if the sternal halves cannot be approximated due to their poor compliance (as in older patients), multiple chondrotomies can be performed. Periosteal flap, obtained from each of the sternal bar, can be rotated and sutured on the midline, representing the posterior wall of the "new sternum." Any remaining gap can be filled by cartilage grafts. Alternatively, synthetic prostheses can be used.

If primary closure is not possible, Gore-Tex, Lactosorb, or artificial bone are usually used to mind the gap with good results, but there is an increased risk of infections, and the use of non-absorbable prosthesis in a developing thorax is a matter of concern [7, 15–17].

In long-term follow-up, some of these patients may develop a mild pectus excavatum.

If pectus excavatum has to be corrected (because of heart compression), the Nuss procedure can be used to repair the defect, with special care during retrosternal dissection, to avoid injuring the pericardium and myocardium [18] (Fig. 20.2).

Postoperative care of children with PC is often complicated by respiratory insufficiency and the prolonged need for ventilator support. Cardiac postoperative complications include residual shunt and low cardiac output syndrome or cardiac insufficiency. Avoiding high postoperative intra-abdominal and intrathoracic pressures is fundamental, and therefore, the use of intra-abdominal pressure monitoring is crucial in critically ill children [19].

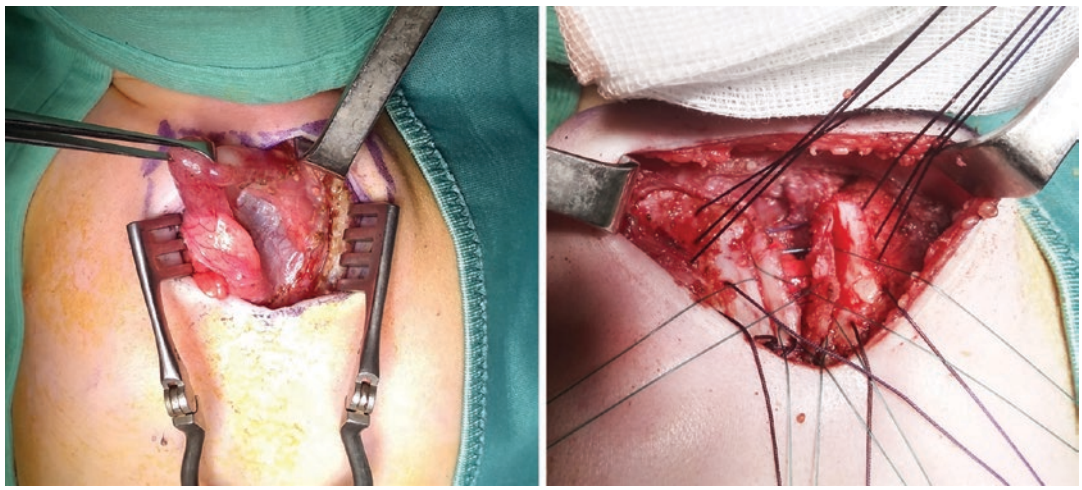


Fig. 20.2 Thymectomy on the left side and, on the right, the direct closure of the sternum

20.5 Conclusion

The survival rate for children with SC is excellent, but if SC is associated with PC, the survival was reported to be about 37%, depending primarily on the type and severity of associated malformations. However, the survival rate has improved over the years up to 61%, thanks to advances in pediatric surgery and neonatal intensive care. The mean age at which patients underwent surgical operation is a predictor of survival, and mean age at surgery of survivors is seen to be 9 months [7, 20]. Postoperative care of children with PC is generally complicated by respiratory insufficiency, whereas late mortality is usually due to cardiac dysfunction, infections, or adhesive intestinal obstruction [19, 21]. Advances in fetal surgery will probably affect the treatment options and outcomes for children with sternal cleft and Cantrell syndrome.

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Part VI

Oncology

Main Thoracic Tumors in Pediatric Age

21

Stefano Avanzini, Federico Palo,
Vittorio Guerriero, and Girolamo Mattioli

21.1 Introduction

Thoracic tumors in pediatric age mainly arise from the mediastinum. Tumors arising from the bone and cartilage of the chest wall are rare. Primary lung and bronchial tumors are exceptionally rare, while metastases are more frequent. Thoracic tumors are most commonly discovered incidentally on chest radiographs. Large thoracic masses can cause compression of adjacent structures. Patients may have airway compression or cardiovascular compromise (Fig. 21.1) [1]. The location of the mass, its effect on adjacent mediastinal organs, and its radiological internal characteristics (calcification, fat, water, and necrosis) can help in establishing a differential diagnosis and clinical planning [2].

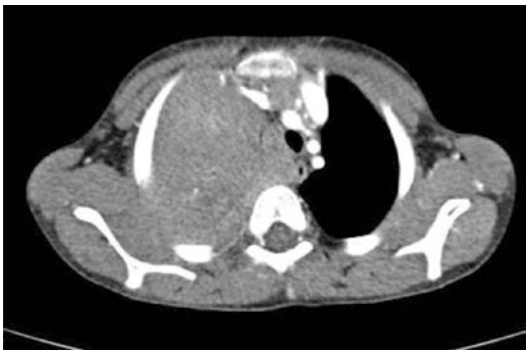

Fig. 21.1 Huge thoracic tumor with airway displacement

21.2 Classification

Classification of thoracic tumors is mainly related to the site of origin of the mass. They can be grossly divided into:

- Mediastinal tumors
  - Anterior mediastinum
  - Middle mediastinum
  - Posterior mediastinum
- Lung tumors
  - Primary
  - Secondary
- Chest wall tumors
  - Primary
  - Secondary
- Airways tumors

S. Avanzini (✉)
Pediatric Surgery, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: stefanoavanzini@gaslini.org

F. Palo · G. Mattioli
Pediatric Surgery, IRCCS Giannina Gaslini Genoa, University of Genoa, DINOGMI, Genoa, Italy
e-mail: girolamomattioli@gaslini.org

V. Guerriero
Pediatric Surgery and Airway Team, IRCCS Giannina Gaslini, Genoa, Italy
e-mail: vittorioguerriero@gaslini.org

G. Mattioli et al. (eds.), *Pediatric Thoracic Surgery*, https://doi.org/10.1007/978-3-030-74668-1_21

21.2.1 Mediastinal Tumors

Mediastinal masses in children are a heterogeneous group of asymptomatic or potentially life-threatening congenital, infectious, or neoplastic lesions that present complex diagnostic and therapeutic dilemmas.

The mediastinum is located in the central portion of the thorax, between the two pleural cavities, the diaphragm and the thoracic inlet [3]. The classification of Fraser et al. [4] divides the mediastinum into the traditional anterior, middle, and posterior compartments based on the lateral chest radiograph. The anterior mediastinum is defined as the region posterior to the sternum and anterior to the heart and brachiocephalic vessels. It contains the thymus, fat tissue, and lymph nodes. The middle mediastinal compartment is located posterior to the anterior mediastinum and anterior to the posterior mediastinum. This space contains the heart and pericardium, the ascending and transverse aorta, the brachiocephalic vessels, the vena cava, the main pulmonary artery and veins, the trachea, bronchi, and lymph nodes. The posterior mediastinal compartment is located posterior to the heart and trachea and extends posteriorly to the thoracic vertebral margin and includes the costovertebral space. It contains the descending thoracic aorta, esophagus, azygos veins, autonomic ganglia and nerves, thoracic duct, lymph nodes, and fat [5]. Mediastinal masses are usually assigned to a single mediastinal compartment to limit the differential diagnosis. Because tumors arise from normal structures that may be located within multiple regions, a given mass can develop in any compartment.

21.2.1.1 Anterior Mediastinum

Several benign and malignant conditions may arise in the anterior mediastinum (see Box 21.1).

Box 21.1 Pediatric Anterior Mediastinal Masses. *Most Frequent Diseases

Pediatric anterior mediastinal masses	
Thymus	**Normal thymus***
	Thymic cyst
	Thymomegaly
	Thymoma
	Thymic hemorrhage
Adenopathy	**Infectious adenopathy***
	Lymphoma or leukemia*
	Sarcoidosis
	Castleman disease
	Rosai–Dorfman disease
Solid tumors	**Germ cell tumors***
	Thyroid or parathyroid tumors
	Hamartoma
	Vagus-phrenic nerve tumors
	Hemangioma
	Sternal tumors
Infections	Mediastinitis
	Sternal osteomyelitis or abscess
Vascular abnormalities	Vascular malformations
	Aneurysm
Other	Histiocytosis
	Morgagni's hernia
	Hematoma
	Extension of middle mediastinal mass

Thymus

Thymic disorders are rare in the pediatric population. Hyperplasia of the thymus is the most common process to involve the thymus gland in infants and children. The hyperplastic gland usually maintains the radiographic characteristics of the normal thymus. Thymic enlargement rarely causes neonatal respiratory distress but should be considered in the differential diagnosis of marked tachypnea in the neonatal period [6]. Thymomas account for up to 4% of pediatric mediastinal neoplasms [7, 8]. Thymoma is associated with four organ-specific autoimmune diseases: (1) myasthenia gravis (2) type 1 diabetes mellitus, (3) autoimmune hepatitis, and (4) Hashimoto's thyroiditis [7].

Lymphoma

Lymphomas are the third most common group of cancers in children and adolescents, accounting for approximately 13% of newly diagnosed cancers in this age group. Non-Hodgkin's lymphoma represents approximately 60% of these diagnoses, and Hodgkin's disease accounts for the remainder [9–12]. Lymphomas are the most com-

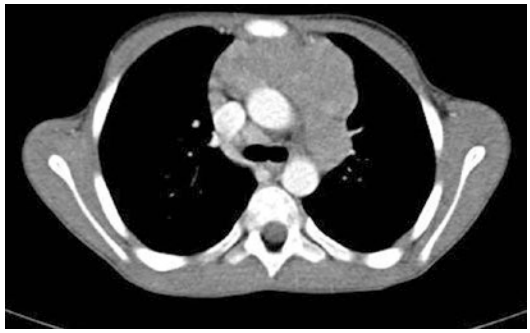

Fig. 21.2 Anterior mediastinal mass (lymphoma)

mon cause of masses in the pediatric mediastinum (Fig. 21.2). More than 50% of children with lymphoblastic lymphoma present with an anterior mediastinal mass, and more than one-third of all patients with non-Hodgkin's lymphoma have their primary sites in the mediastinum. Hodgkin's disease also frequently involves this anatomic compartment with approximately two-thirds of all pediatric cases manifesting mediastinal adenopathy [13]. Being radiological and clinical presentation similar in different lymphoma subtypes, biopsy (either image-guided needle biopsy or properly surgical) may be the only possibility to diagnose and classify the tumor and consequently address the appropriate chemotherapy.

Germ Cell Tumors

Germ cell tumors are the third most common neoplasm of the mediastinum after lymphoma and neurogenic tumors. Most often, they arise within the anterior mediastinum near the thymus gland. A small subset of germ cell tumors arises from other mediastinal compartments. Germ cell tumors account for 6–18% of mediastinal tumors and comprise only 1–3% of all germ cell tumors [14, 15]. Two theories have been proposed to explain the development of malignant nonseminomatous germ cell tumors (MNSGCT). One is that mediastinal germ cell tumors originate from germ cells that mismigrate during embryogenesis, and the other theory is that they originate from germ cells that are widely distributed during embryogenesis. Both theories could explain the central location of germ cell tumors in the mediastinum, retroperitoneum, sacrococcygeal area, and in the central nervous system [16, 17].

Teratomas are the most common mediastinal germ cell tumor and are divided into mature, immature, and mixed malignant types. Nonteratomatous tumors include seminoma, yolk sac tumor, embryonal carcinoma, choriocarcinoma, and mixed types. A malignant germ cell tumor is a complex tumor of varied histology with frequent coexistence of benign elements. Lesions often have incomplete regression with chemotherapy alone, and tumor resection may be undertaken at diagnosis or after primary chemotherapy [18].

The clinical picture is nonspecific. Germ cell tumors are large and produce respiratory distress caused by tracheobronchial compression. Most children have a subacute course that may span several weeks or longer. Germ cell tumors can be seen in patients with Klinefelter's syndrome and may present with precocious puberty [19].

With chest radiography, teratomas can be rounded or lobulated and can be large in size. Up to 26% of teratomas exhibit calcification [20]. On CT scan, teratomas are multilocular cystic tumors with a variable wall thickness [21]. The combination of fluid, soft tissue, calcium, and fat attenuation in the anterior mediastinal mass is highly specific for teratoma [5]. Seminoma generally presents as a bulky lobulated mass, which uncommonly invades adjacent structures but can metastasize to regional lymph nodes and bone [22–24]. Seminoma rarely calcifies. Nonseminomatous malignant germ cell tumors are radiographically large and irregular with extensive heterogeneous areas of low attenuation on CT caused by necrosis, hemorrhage, and cyst formation [23]. Germ cell tumors appear on MR imaging as masses of heterogeneous signal intensity. The most striking difference between mediastinal and gonadal nonseminomatous germ cell tumors concerns prognoses. Overall, 5-year survival in MNSGCT is about 40%, which is much lower than in gonadal non-seminomatous germ cell tumor and is a unique feature of MNSGCT [24, 25].

The current standard treatment in MNSGCT is chemotherapy combined with post-chemotherapy residual mass excision. In most cases, surgery is technically challenging. Adhesion and invasion of surrounding structures are usually found during exploration, and vascular involvement often makes complete excision impossible. Total resection includes en bloc resection of the primary

lesion and the complete excision of metastatic lesions. Given poor alternative options in this aggressive disease, surgery may also be offered even to patients with increasing post-chemotherapy markers if complete resection can be accomplished. Unfortunately, hope for cure remains feeble in this subset of patients and supports ongoing investigation of other salvage modalities for primary treatment failure [26].

After the introduction of cisplatin-based chemotherapy, followed by surgical resection, survival in cases of MNSGCT improved dramatically, and this multimodality treatment has become the standard treatment for MNSGCT [27, 28].

21.2.1.2 Middle Mediastinum

Benign and malignant conditions may arise in the middle mediastinum (sometimes extending from the anterior mediastinum), the majority and more relevant to the aim of this chapter being adenopathies (see Box 21.2).

Box 21.2 Pediatric Middle Mediastinal Masses. * Most Frequent Diseases

Pediatric middle mediastinal masses	
Adenopathy	**Infectious adenopathy (e.g., tuberculosis)*** **Metastatic disease*** **Lymphoma or leukemia*** Sarcoidosis Castleman disease Rosai-Dorfman disease
Solid tumors	Thyroid or parathyroid tumors Vagus-phrenic nerve tumors Cardiac tumors Hemangioma Hamartoma
Infections	Mediastinitis
Vascular abnormalities	Vascular malformations Vascular rings Aneurysm
Other	**Bronchopulmonary foregut malformations (i.e., esophageal duplication cyst, neuroenteric cyst)*** Histiocytosis Hematoma Diaphragmatic rupture Pancreatic pseudocyst Esophageal hernia Achalasia, chalasia Pericardiac cyst

Lymph node groups may be visible on chest radiography when they become enlarged. The etiology of lymph node enlargement is extensive. In fact, most middle mediastinal masses are caused by either adenopathy or bronchopulmonary foregut malformations. The most frequent causes of adenopathy are lymphoma; leukemia; tuberculosis; histoplasmosis; sarcoidosis; cystic fibrosis; infectious mononucleosis; Langerhans' cell histiocytosis; Castleman disease; and metastatic neoplasms, such as neuroblastoma in the young child and testicular carcinoma in the teenager that metastasize to mediastinal nodes [29].

21.2.1.3 Posterior Mediastinum

Of all pediatric mediastinal masses, 30–40% occur in the posterior mediastinum [5]. Most (85–90%) of these masses are of neurogenic origin [30]. CT and MR imaging are used to stage the extent of the disease, establishing a differential diagnosis list, and help in judging the efficacy of treatment (see Box 21.3).

Box 21.3 Pediatric Posterior Mediastinal Masses. *Most Frequent Diseases

Pediatric posterior mediastinal masses	
Ganglion cell tumors	**Peripheral neuroblastic tumors*** **• Neuroblastoma** **• Ganglioneuroblastoma** **• Ganglioneuroma**
Other nervous system tumors	Nerve sheath tumors (schwannoma, neurofibroma) Paraganglioma
Adenopathy	Metastases Infectious adenopathy Sarcoidosis Castleman disease Rosai-Dorfman disease
Solid tumors	Osseocartilaginous tumors Thoracic duct cyst Hemangioma
Infections	Mediastinitis Vertebral osteomyelitis Diskitis
Vascular abnormalities	Vascular malformations Aneurysm Dilated azygous system

Pediatric posterior mediastinal masses	
Other	Hematoma (secondary to fracture) Bochdaleck's congenital diaphragmatic hernia Extramedullary hematopoiesis Lateral meningocele Extension of normal thymus Histiocytosis

Neurogenic Tumors

Neurogenic tumors or ganglion cell tumors arise from the sympathetic chain ganglia. These lesions range from malignant masses (neuroblastoma) to benign tumors (ganglioneuroma). Ganglioneuroblastoma has components of both ganglioneuroma and neuroblastoma. All three histologic types are radiographically indistinguishable. Therefore, the appropriate differential diagnosis is partly determined by the patient's characteristics, blood and urine examinations, and mostly by biopsying the tumor.

Neuroblastoma is the most common extracranial solid tumor in children. It represents 10% of all childhood cancers and, because of its potentially highly aggressive nature, accounts for 15% of cancer deaths [31]. After the abdomen, the thorax is the second most common location of neuroblastoma (15%) followed by the neck (1–5%) and the pelvis (2–3%) [32, 33].

Age at presentation is one of the most important criteria when evaluating a patient with a posterior mediastinal mass. Neuroblastoma is a malignancy of young children and is diagnosed at a median age of less than 2 years old and greater than 95% by age 10. In younger patients (less than 5 years old), neuroblastoma is twice as common in boys as girls. As they get older, however, it affects both sexes equally. Fetal or congenital neuroblastoma may even be seen on prenatal ultrasonography. The median age of presentation of ganglioneuroblastoma is 5.5 years of age. Mature ganglioneuroma presents even later in childhood, most often after 10 years of age [31]. Furthermore, it is possible for the immature cells found in neuroblastoma and ganglioneuroblastoma to undergo a spontaneous maturation process and follow the benign course of ganglioneuroma [34].

Patients with thoracic neuroblastoma can be asymptomatic; masses are found incidentally on chest radiographs. When symptoms do occur, they can be related either to the primary tumor or to the metastatic disease. Local mass effect or intraspinal extension can lead to symptoms of respiratory distress or cord compression, respectively. Neuroblastoma can secrete catecholamines, such as vanillylmandelic acid and homovanillic acid. In such a scenario, high levels of these catabolites may be detected in the urine, thus allowing for a proper diagnosis [30, 31]. Finally, patients with a widely disseminated disease can present with constitutional symptoms, such as fever, weight loss, and bone pain.

With conventional radiographs of the thorax, ganglion cell tumors appear as paraspinal well-defined masses. Chest wall involvement and rib remodeling are uncommon but possible with neuroblastoma. Intraspinal extension includes widening of the intervertebral foramina or pedicle erosion. Because the skeletal system is the most common site of metastasis, an initial skeletal survey with a combination of conventional radiographs and bone scintigraphy, including iodine 123 m-iodobenzylguanidine (123I-MIBG), is an essential part of the evaluation for any patient with the diagnosis of neuroblastoma. CT and MR examination are routinely employed to assess thoracic neuroblastoma (Fig. 21.3). Contrast enhancement may highlight intratumoral areas of necrosis or hemorrhage.

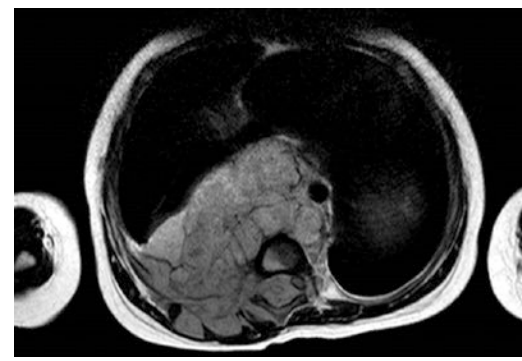

Fig. 21.3 Posterior mediastinal mass (neuroblastoma), with vascular encasement (aorta) and with spinal canal invasion

Calcification can be seen in up to 80% of patients with neuroblastoma [35]. Imaging provides information regarding the extent of tumor, regional invasion, metastatic adenopathy, and vascular encasement. The concept of "surgical risk factors" lately named "image-defined risk factors" (IDRFs) was introduced in 1994 and routinely applied since 2005 [36, 37]. The IDRFs and the INRGSS are designed for use at the time of diagnosis, but they may also be used at reassessments during treatment. The exact preoperative evaluation of IDRFs is mandatory to stage the patient and therefore plan the appropriate treatment (see staging). If one or more of these features have been documented, presurgical chemotherapy should be administered in order to shrink the tumor and enable safe tumor resection [38]. Thoracic IDRFs include:

- Cervicothoracic junction:
  - Tumor encasing brachial plexus roots
  - Tumor encasing subclavian vessels and/or vertebral and/or carotid artery
  - Tumor compressing the trachea
- Thorax:
  - Tumor encasing the aorta and/or major branches
  - Tumor compressing the trachea and/or principal bronchi
  - Lower mediastinal tumor, infiltrating the costovertebral junction between T9 and T12

The primary tumor can also spread through the neural foramina and extend through it into the spinal canal creating a classic dumbbell. This appearance is seen in up to 28% of patients with thoracic neuroblastoma [31]. 123I- or 131I-MIBG, an analog to catecholamine precursors, can concentrate in neuroblastic cells. MIBG localizes in primary sites of neuroblastoma and in metastatic sites in 90–95% of patients [39–41]. MIBG scintigraphy should be performed in all newly diagnosed patients. MIBG findings can result in the detection of metastases that are not evident by other imaging studies. Determination of MIBG avidity can influence the choice of follow-up evaluation [42].

The role of PET is gaining importance in the management of patients with neuroblastoma. FDG-PET may offer advantages over MIBG scintigraphy in detecting small lesions or localizing the extent of the disease. In addition, PET can detect lesions in the liver, which are obscured in MIBG scintigraphy by normal MIBG uptake by the liver. PET cannot demonstrate lesions in the cranium because of normal brain avidity [34].

The staging of neuroblastoma and ganglioneuroblastoma is radiologically or surgically determined by the local extent of disease and locating the sites of metastatic involvement.

The International Neuroblastoma Risk Group (INRG) classification system was introduced in 2009 first alongside the International Neuroblastoma Staging System and then progressively gaining clinical relevance with the advantage to facilitate the comparison of risk-based clinical trials conducted in different regions of the world by defining homogenous pretreatment patient cohorts [43]. In the INGRSS, locoregional tumors are staged L1 or L2 based on the absence or presence of one or more IDRFs, respectively. Metastatic tumors are defined as stage M, except for stage MS, in which metastases are confined to the skin, liver, and/or bone marrow in children younger than 18 months of age.

Neuroblastoma prognosis varies tremendously based on the stage and biological features of the tumor. Treatment varies depending on the risk group and can range from surgery alone for localized tumors to aggressive multimodality treatment for MYCN-amplified tumors. Although surgery plays a role in the diagnosis and management of all stages of neuroblastoma, the importance of that role, especially the extent of resection, in high-risk neuroblastoma continues to evolve. In the past 5 years, there have been several advances in neuroblastoma surgery. Studies have demonstrated that patients with low-risk disease can be treated with surgery alone, and in a subset of patients who are neonatally diagnosed with adrenal tumors, surgery can be avoided in 80% [44–46]. In contrast to its pivotal role in localized disease, surgery has a somewhat controversial role in metastatic disease. However, given the high incidence of local relapses, the current indi-

cation in most treatment protocols is resection of the primary tumor after debulking at metastatic sites [46–48]. Since neuroblastoma has an elevated tropism for lymphatic vessels and lymph-node infiltration, surgical tumor resection should include exploration of locoregional lymph nodes, especially in abdominal and pelvic locations. In the case of paravertebral locations with spinal canal invasion through intervertebral foramina, laminectomy is indicated only in the presence of rapidly progressive neurological symptoms, as chemotherapy can rapidly reduce the volume of the tumor and relieve compression [49].

Nerve Sheath and Nerve Tumors

Nerve sheath tumors are either schwannomas or neurofibromas. Histologically, schwannomas are encapsulated without nerve fibers running through the tissue. Conversely, neurofibromas are unencapsulated with nerve fibers running through the tissue. These nerve sheath tumors are most commonly benign and asymptomatic and are rarely seen in less than 20 years of age [50]. They often arise from intercostals or sympathetic nerves and are more common in patients with neurofibromatosis type II. Schwannomas constitute 75% of nerve sheath tumors.

Malignant degeneration of these neurofibromas and schwannomas is rare in the pediatric population and involves less than 5% of nerve sheath tumors. Benign lesions can either be observed or resected; however, malignant lesions require complete surgical resection for cure. For malignant tumors, adjuvant chemotherapy and radiation do not seem to improve survival. Local recurrence is common, and the prognosis is poor [51].

Paragangliomas

Although most pediatric posterior mediastinal masses are of ganglion cell or nerve sheath or nerve origin, other nervous tissue tumors must be considered when formulating a complete differential diagnosis. Paragangliomas or extra-adrenal pheochromocytomas are rare tumors of chromaffin cells of the sympathetic nervous tissue that can be seen in the posterior mediastinum within the paravertebral sulcus. Patients with these lesions often present with signs of catecholamine excess. Less than 2% of these tumors are malignant [52]. Treatment consists of surgical resection; however, recurrence can occur, and close follow-up after excision is recommended.

Nonneurogenic Posterior Mediastinal Masses

Extramedullary hematopoiesis is often clinically asymptomatic; however, it may present as signs of spinal cord compression. Extramedullary hematopoiesis is seen in hematologic disorders, most commonly thalassemia. The actual pathogenesis of this disorder, however, is unknown. Bilateral paraspinal masses with smooth margins are the classic presentation on chest radiographs. The soft tissue mass may contain fat and is almost always seen within the lower thorax. These masses are either observed if clinically silent or maybe surgically resected.

Lipomatosis is a deposit of mature fat in the extrapleural and mediastinal spaces, commonly associated with long-term steroid administration [53]. On CT or MR imaging, the appearance is that of the normal subcutaneous fat.

Vascular masses, including hemangiomas (true neoplasms) and vascular malformations, can occur in the posterior mediastinum, although they rarely isolate to the posterior mediastinum. The CT or MR imaging appearance depends on the type of vascular malformation (cystic spaces, large blood vessels, fatty components) or stage of hemangioma. Hemangiomas densely enhance in the proliferative stage, with eventual fibrofatty replacement during involution.

The differential diagnosis of nonneurogenic posterior mediastinal masses also includes primary soft tissue malignancies, such as Ewing's sarcoma, germ cell tumor, and rhabdomyosarcoma. All these malignancies can arise in the paraspinal area and can dumbbell into the spinal canal [54, 55]. Adenopathy, both infectious and metastatic, is also a consideration.

21.2.2 Lung Primary and Secondary Tumors

Primary pulmonary tumors are rare in infants and children. The spectrum of pediatric lung tumors is quite different from that occurring in adults.

Most pulmonary neoplasms in children are malignant in nature, and metastatic lesions are far more common than primary malignancy. This latter group includes primary lung parenchymal tumors and airways tumors (see the following chapter).

21.2.2.1 Pleuropulmonary Blastoma

Pleuropulmonary blastoma (PPB) is a rare mesenchymal childhood malignant neoplasm. Three types are described based on morphology and increasing malignant behavior. Type I is purely cystic and mostly seen in younger children. Type I PPB resembles congenital pulmonary adenomatoid malformation (CPAM) clinically and radiologically and cannot be differentiated without histological examination (Fig. 21.4). Type II PPBs are mixed cystic and solid, while type III tumors are predominately solid. Both type I and II PPB occur in older children and often arise from preexisting cystic lesions. Some evidence suggest that type I tumors may evolve into the more malignant types II and III if untreated [56]. Cough, fever, and sometimes pain in the chest suggesting a respiratory infection are often the first symptoms. The chest radiographs may be interpreted as "pneumonia," delaying the diagnosis. Pneumothorax is another common presentation, especially in younger patients. Malignant potential increases with the solid component, and more than 20% of patients present with metastatic disease [57]. The tumor is usually located at the periphery of the lung, but it may also be located in extrapulmonary locations, such as the mediastinum, diaphragm, and/or pleura. Since most of the lung tumors are located peripherally, resection is usually possible by segmental or lobar resection. However, since the limit between the lesion and the normal parenchyma may be difficult to determine grossly and because of the high risk of local recurrence and metastatic spread, the surgical procedure of choice for parenchymal PPB is lobectomy. The use of multimodal neoadjuvant chemotherapy and radiation following surgical resection has shown promising results in a few patients with extensive disease and dissemination. Despite aggressive treatment protocols, the prognosis for patients with PPB is not good, with 5-year survival rates of 83% for type 1 and 42% for types 2 and 3. Furthermore, it appears that type II and III lesions have a tendency to recur, even at remote or contralateral sites, despite an apparently complete resection of the primary tumor [58]. It is not known whether the tumor can develop in preexisting benign congenital cystic lung disease or whether the cysts in these cases are type I PPB from the outset. The latter opinion has been favored recently, especially since PPB has been identified in fetuses and neonates [59].

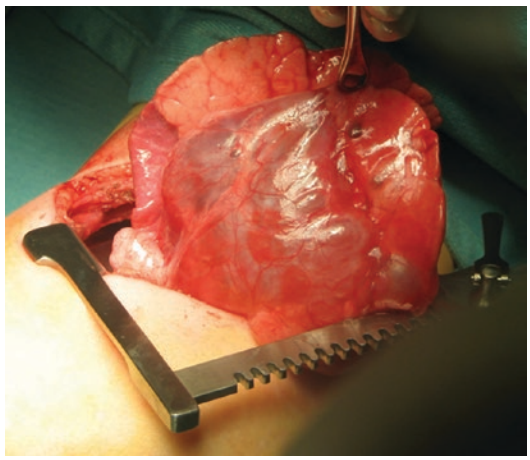

Fig. 21.4 Surgical resection of a macrocystic lung lesion (differential diagnosis should include PPB type I and macrocystic CPAM)

21.2.2.2 Secondary Lung Tumors

In recent decades, significant progress has been made in the treatment of pediatric solid tumors, with current overall survival rates of 75–90% in nonmetastatic tumors. Unfortunately, 10–30% of children with solid tumors present with metastases, and an additional 15–20% relapse at distant sites [60]. Advances in the treatment of metastatic disease, however, have not mirrored those of nonmetastatic solid malignancies, with overall survival ranging from 20% to 70%, depending primarily on histology [60]. As metastasis is a disseminated process, treatment depends on effective systemic therapy, but surgical resection can sometimes be therapeutic [61].

Computed tomography (CT) scan is nowadays the gold standard for the identification of pulmo-

nary nodules. However, the limitations of CT are still apparent in multiple pediatric solid tumors, including the fact that there are generally no findings pathognomonic for specific histologies, both neoplastic and non-neoplastic (Fig. 21.5). Although the high sensitivity of CT can be beneficial, its lack of specificity with respect to differentiating malignant from benign nodules can lead to false-positive interpretations, resulting in unnecessary anxiety, surgery, and/or overtreatment if a confirmatory biopsy is not performed [61]. Additional difficulties arise when trying to localize the CT-identified lesions for diagnostic or therapeutic resection, particularly if a minimally invasive approach, such as thoracoscopy, is planned. While superficial lesions can be seen intraoperatively on visual inspection and larger, firmer lesions can be palpated with instruments, many deeper, smaller, softer lesions can easily be missed, regardless of the surgical approach. Given that the goal of metastasectomy is resection with maximal preservation of normal lung tissue, lobectomies or segementectomies are not a solution to this problem. Multiple techniques have been used to overcome this problem, including preoperative marking with wires, coils, or dye, and localization with intraoperative ultrasound [62–64]. All these strategies are useful, but each has its drawbacks. Dyes spread along the pleura, coils, and wires can be inaccurately placed or dislodged, and the accuracy of ultrasound is limited by lesion depth and the amount of air in the lung. Despite the risk of dislodgement, most authors favor preoperative wire or coil placement when attempting to localize a difficult lesion in the lung.

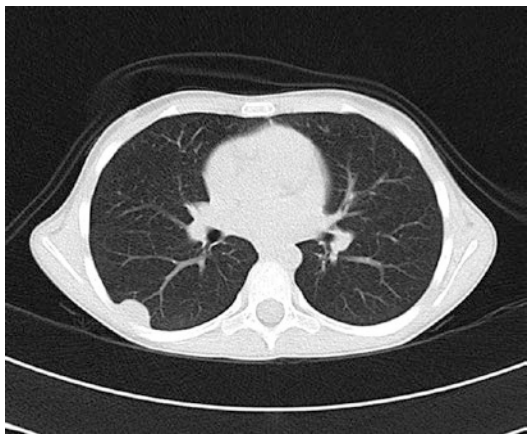

Fig. 21.5 Wilms tumor right lung metastasis

21.2.2.3 Osteosarcoma

Osteosarcoma is the most common pediatric bone tumor. Twenty percent of these patients present with metastasis at diagnosis, and another 22% eventually develop metastasis at some point. Pulmonary metastases comprise 85% of these metastases. While the overall survival of patients with osteosarcoma has improved to 75% in recent trials, survival for metastatic osteosarcoma is still only 17–34%. Many studies have found that complete surgical resection of primary and metastatic disease is essential for survival in osteosarcoma [61]. Good prognostic factors in metastatic osteosarcoma include diagnosis of metastasis after treatment rather than prior to or during chemotherapy, longer disease-free interval between treatment and relapse, fewer metastatic lesions, better histologic response to preoperative chemotherapy, and the ability to clear all metastatic disease surgically. Metastasectomy in osteosarcoma should be attempted whenever complete surgical resection of the primary and metastatic sites is possible. The presence of miliary disease and/or hilar node or pleural involvement can be considered relative contraindications, depending on the ability to resect all lesions and maintain adequate pulmonary function. The use of an open technique with exploration and palpation of both lungs has been supported by overwhelming evidence that complete resection of all detectable disease is necessary for survival, because of the finding that pre-operative CT misses up to a quarter of viable osteosarcoma metastases found by palpation, and by evidence that up to 60% of patients with unilateral CT lesions have contralateral metastases at exploration. Unfortunately, no studies to date have attempted to identify the ideal open approach from among the available options of a median sternotomy, transverse sternotomy, synchronous bilateral or staged bilateral thoracotomies using posterolateral muscle-sparing, vertical transaxillary, or lateral incisions. While sternotomy allows access to both lungs at

once, the posterior lung and left lower lobe are difficult to evaluate. Despite the exposure that thoracotomy provides, its use necessitates two incisions, and usually two separate surgeries, as it is better tolerated when staged [65].

21.2.2.4 Wilms Tumor

Approximately 10% of Wilms tumor patients present with pulmonary metastasis although they still have high overall survival rates [66]. Although burdened by a percentage of long-term sequelae and a significant risk of developing a second tumor, in the United States, these pulmonary nodules have traditionally been treated with whole-lung radiation with good outcomes [67]. In Europe, therapeutic metastasectomy has been used to avoid the long-term effects of lung radiation. The International Society of Pediatric Oncology (SIOP) protocol 93-01 allowed for pulmonary metastasectomy after initial chemotherapy. If complete remission is achieved by chemotherapy alone or with chemotherapy and surgery, patients continue on similar chemotherapy and did not receive lung radiation [68]. The recently closed Children's Oncology Group (COG) trial AREN0533 also eliminated lung radiation for patients who achieved complete remission of lung disease after 6 weeks of 3-drug chemotherapy and encouraged biopsy of lung nodules after initial chemotherapy to ensure that patients did not receive unnecessary lung radiation. Overall, the use of surgery in the diagnosis and treatment of pulmonary disease in Wilms tumor is increasing. The upcoming COG high-risk Wilms tumor trial will incorporate the use of metastasectomy to achieve pulmonary complete remission after initial chemotherapy, with the goal of obviating the need for lung radiation, as has been done in the SIOP protocol. With the current diagnostic role of surgery, minimally invasive techniques can be used when complete sampling of the lesions is possible.

21.2.2.5 Hepatoblastoma

Approximately 20% of patients with hepatoblastoma present with pulmonary metastases. Patients with metastases have a much lower survival rate (25–50%) compared to those without [69]. While early case reports showed the potential for cure following metastasectomy, initial chemotherapy trials also showed the possibility of complete resolution of lung metastases with chemotherapy alone. Two larger Japanese trials showed the importance of this combined approach and emphasized the use of metastasectomy for residual lung disease after chemotherapy [70, 71]. The strategy of combining chemotherapy and metastasectomy for the residual disease is still used in all major hepatoblastoma cooperative trials for patients with pulmonary metastatic disease at diagnosis. The resection of any residual disease in the lungs is of utmost importance before local control for PRETEXT III and IV patients who require liver transplantation due to the need for post-transplant immunosuppression. Contraindications to metastasectomy include an inability to achieve a complete resection while preserving adequate lung function and the presence of uncontrolled disease at the primary site. There is no contraindication to minimally invasive techniques if complete resection can be accomplished.

21.2.2.6 Neuroblastoma

Among patients with neuroblastoma, pulmonary metastasis at diagnosis is rare. The International Neuroblastoma Risk Group Study most recently reported an incidence of 3.6% [72]. However, all of these might be underestimates, as detailed lung imaging was not obtained in the majority of these patients. The likelihood of metastasis in general and lung metastases, in particular, is higher in patients older than 1 year and with MYCN amplification (denoting a higher risk group). Patients with lung metastases are much more likely to have metastases to the CNS and other locations. Regardless of the metastatic burden or location of metastases, surgery should be reserved for diagnosis only. Biopsy of the most easily accessed site, whether primary or metastatic, for initial diagnosis or recurrence is recommended.

21.2.2.7 Rhabdomyosarcoma

Overall survival for metastatic rhabdomyosarcoma (RMS) is poor. One early mixed-histology case series reported that patients with pulmonary

metastases from RMS are 35 times more likely to relapse in the lung than patients with lung metastases from other sarcomatous histologies [73], and other reports confirmed a dismal outcome [74]. The largest European study included 174 patients with metastatic RMS, 55% of whom had metastases to multiple organ systems. The unfavorable primary site, bone or bone marrow involvement, and age <1 or >10 years were independent, unfavorable risk factors. Patients with 0 or 1 of these factors had an overall survival of 47%, whereas overall survival was 9% for those with two or more risk factors [75]. A more recent COG report divided patients into groups, as the previous European trial did, and found that patients with 0 or 1 risk factor (age <1 or >10, unfavorable site, bone or bone marrow involvement) had 3-year event-free survival of 69%, which is an improvement over earlier trials. Unfortunately, patients with 2 or more risk factors, which constitute the majority of metastatic RMS patients, still only have a 3-year event-free survival of 20% [76]. Given the poor outcome and good response to chemotherapy and radiation, metastasectomy in rhabdomyosarcoma should only be performed for diagnosis, and minimally invasive techniques can be used when appropriate.

21.2.2.8 Non-Rhabdomyosarcoma Soft Tissue Sarcoma (NRSTS)

This family of sarcomas includes alveolar soft part sarcoma, synovial sarcoma, chondrosarcoma, and malignant fibrous histiocytoma, among others. These tumors have a propensity to metastasize to the lung and are generally resistant to chemotherapy and radiation. The rarity of these tumors makes their study difficult. Based on resistance to other treatments, metastasectomy has been recommended for this family of tumors whenever complete resection of all diseases is possible [77]. CT is the modality of choice for the diagnosis of these lung lesions, and because of their consistency, these tumors may be difficult to palpate. Localization techniques described earlier may be advisable for deeper lesions regardless of open or minimally invasive approach.

21.2.2.9 Ewing Sarcoma

Ewing sarcoma is a chemo- and radiosensitive tumor, which makes the assessment of the utility of surgery more difficult. A recent Polish study, published in 2016, reviewed 38 patients with Ewing sarcoma and isolated lung metastases treated with modern multi-modal therapy from 2000–2014. Patients with a radiographic response to initial chemotherapy had improved event-free survival, but no effect of metastasectomy was observed [78]. Given the multitude of conflicting reports hampered by poorly controlled data, there is no reliable evidence that metastasectomy in Ewing sarcoma is of therapeutic benefit. However, with the 47% rate of negative biopsy in patients with small to moderate lung lesions, it can still play an important role in diagnosis, perhaps saving some patients from intensified therapy or lung radiation.

21.2.2.10 Adrenocortical Carcinoma

Adrenocortical carcinoma is a rare chemotherapy and radiation-resistant tumor. Although pediatric case series examining the effect of pulmonary metastasectomy do not exist, there is ample evidence in the adult literature that this procedure is beneficial and can enhance long-term survival [79]. Case reports confirm the ability of metastasectomy to produce long-term survival in the pediatric population [80, 81]. Pulmonary metastasectomy should be performed in any patient with metastatic adrenocortical carcinoma in who complete resection is possible. Although there is no contraindication to minimally invasive resection, there are ample data from adults that these tumors are at high risk of rupture during dissection and removal and that spillage can lead to implants and carcinomatosis. The implications of spillage are heightened as there is little useful treatment other than surgery, so the surgeon must make every attempt to dissect and remove the tumor intact.

21.2.3 Bronchial Tumors

Primary tracheobronchial tumors represent a heterogeneous group of rare tumors with an overall

incidence of 0.0049 per 100 thousand children (about 0.2% of all tumors in this age group) [82]. Because of nonspecific clinical presentations showing heterogeneous symptoms, diagnosis is often difficult, and the airway involvement can lead progressively to a bronchial or tracheal obstruction [83].

Due to the rarity of these tumors, oncological guidelines on preoperative workup, treatment, and follow-up are lacking. Surgical resection often seems to be the treatment of choice, while the endoscopic approach is recommended only in highly selected cases depending on tumor localization and histological type. Chemotherapy and radiotherapy are usually indicated only for the management of tumor relapse [83]. Tumor histology is the main factor determining the survival rate with a better survival reported for carcinoids and mucoepidermoid carcinoma. The better prognosis of these tumors is also related to the intraoperative findings of negative lymph nodes, and survival is higher when lymphadenectomy and a lesser extensive surgery are performed [84].

Symptoms are usually connected to the site and type of the tumor. Obstructive symptoms are prevailing in case of severe upper airway obstruction (>50% of the lumen) with stridor, wheezing, and dyspnea; cough is very common, expression of mucosal irritation or poor clearance with the accumulation of airway secretions distal to the stenosis; rarely, in case of mucosal ulceration, hemoptysis may be observed. Commonly, clinical presentations of primary tracheobronchial tumors are misdiagnosed as bronchitis, pneumonia, or asthma episodes. Complete or partial lung atelectasis is another frequent occurrence in these patients with bronchial localization. Neuroendocrine tumors as carcinoids can present with the paraneoplastic syndrome (hypotension, diarrhea, and vasomotor flushing in 10–30% of cases); other nonspecific symptoms comprise chest pain and weight loss [83].

Tracheobronchial tumors include both benign and malign lesions: In the first group, the most common histological types are represented by infantile hemangioma and squamous papilloma, while inflammatory pseudotumors, leiomyomas, granular cell tumor, juvenile xanthogranuloma, tracheal lipoblastoma, and laryngotracheal chondromas can occur more rarely. The second group includes carcinoid and mucoepidermoid carcinomas, and less frequently rhabdomyosarcoma, leiomyosarcoma, and adenoid cystic carcinoma [85].

Concerning malignant masses, bronchial carcinoid and mucoepidermoid carcinoma are the most common entities, with a generally good prognosis.

Carcinoid accounts for 80% of all malignant forms. Basing on the mitotic activity rate and the grade of tumor necrosis, they are classified as typical and atypical, with the latter one showing more aggressive behavior and a worse prognosis. Lymph node metastases are frequently described, while local recurrences and distant metastasis rarely occurred [85].

Mucoepidermoid carcinoma looks like an exophytic mass arising from the submucosal bronchial glands. According to cell type, pleomorphism, mitotic index, and the presence of cystic structures, they are classified into low, intermediate, and high-grade tumors. The most common in children is the low-grade type, mainly composed of mucous cells [85].

Rhabdomyosarcoma and leiomyosarcoma together with adenoid cystic carcinoma are the less frequent malignant lesions reported in the pediatric population. The former accounts for 5.8% of all pediatric endobronchial tumors with previous radiation therapy, genetic predisposition, and immunological factors as the main documented risk factors for its occurrence. Leiomyosarcoma is even more sporadic, making up 3.8% of all pediatric forms. Finally, adenoid cystic carcinoma is a very rare lesion in the pediatric population, with an aggressive attitude, because of frequent local relapse and local lymph nodes metastases [85].

A conventional chest X-ray is often performed in these patients, usually detecting nonspecific indirect signs of airway obstruction, as pulmonary collapse, opacity, or hyperinflation. The gold standard for radiological diagnosis is CT scan with intravenous contrast that provides the exact location of the tumor, the intra- and

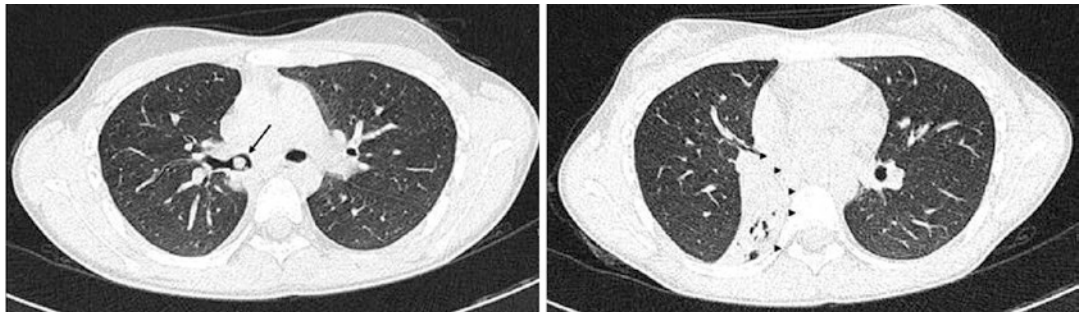

Fig. 21.6 Preoperative CT scan showing an intraluminal mass close to the bifurcation of the right main bronchus in the superior and lower lobar bronchi (*black arrow*) with subsequent atelectasis of the basal segments (*arrowheads*) (with permission from Avanzini S et al. Intraoperative bronchoscopy for bronchial carcinoid parenchymal-sparing resection: a pediatric case report.Pediatr Surg Int. 2012 Jan;28(1):75-8

extra-luminal extension, and the connection with the adjacent organs and vessels (Fig. 21.6). CT also allows 3D reconstruction with the possibility of measurement of the tracheal and bronchial lumen [83]. However, airway endoscopy is essential and commonly used to assess tumor location and obtain tissue sampling. Both flexible fiberoptic endoscopy and rigid bronchoscopy are useful and complementary techniques. Flexible endoscopy is particularly useful to explore the distal airways, and rigid bronchoscopy allows a better view and multiple biopsies or debulking of the tumor while maintaining the patient ventilated. In case of emergency during endoscopy, some procedures can be performed such as hemostasis, tumor debulking, and stenting.

Radical surgical resection of the mass with sparing of the normal lung tissue is the treatment of choice in most cases. Although pneumonectomy and lobectomy have been typically performed for bronchial tumors, parenchyma-sparing procedures, such as sleeve resections and bronchoplasty, are the main procedures performed recently. Moreover, lymph nodes sampling is strictly recommended in case of carcinoid and mucoepidermoid carcinoma because of their capability to metastasize.

Although several reports describe endoscopic resection of tracheobronchial tumors, this approach is still controversial compared to radical surgery. Several limitations and different surgical complications are reported during endoscopic treatment (bleeding, transmural injuries, fiber ruptures, and dislocations). Moreover, repeated procedures are often needed to remove completely the neoplastic mass exposing patients to many anesthesiologic procedures.

In the case of tumors located in the laryngeal and upper trachea region, an anterior transverse neck incision is indicated. During surgery, a temporary intraoperative tracheotomy could be performed. If cartilaginous tissue is not infiltrated, and a clear separation plane is evident, radical excision can be safely performed. Partial resection is mandatory in the case of larynx or tracheal infiltration. Laryngotracheal defect can be repaired by rib grafts. Otherwise, huge tumors require cricotracheal resection with end-to-end anastomosis.

21.2.4 Chest Wall Tumors

Chest wall tumors occur rarely in infants and children, accounting for only 1.8% of all solid childhood tumors. Chest wall neoplasms are primarily of mesenchymal origin and comprise a broad spectrum of benign and malignant lesions, arising from the skeletal or soft tissues of the chest wall. The majority are malignant in nature, with distinct behaviors and varying responses to chemotherapy and radiation. Benign tumors are less common in most series, although they may be underreported. Any growing chest wall mass in children should be evaluated promptly because of the high frequency of malignancy. Most

frequent malignant tumors include Ewing sarcoma, rhabdomyosarcoma, chondrosarcoma, osteosarcoma, and infantile fibrosarcoma [86]. The goals of chest wall resection and reconstruction include complete removal of the local tumor, restoration of adequate protection of the thoracic viscera, restoration of physiologic function providing for adequate lung and chest wall growth, and an acceptable chest wall appearance. Chest wall resection can be achieved via a standard thoracotomy incision, which should include the initial biopsy site. Serratus anterior or pectoralis muscles may need to be excised with appropriate margins. The extent of rib resection depends on the type of tumor. Incisions must be appropriately placed to allow preservation of overlying skin and, if possible, muscle flaps. In most cases, resection of one or multiple ribs is required. The resulting defect can either be closed primarily or may require chest wall reconstruction. Reconstruction of segments of the chest wall is performed to protect underlying structures, to obtain chest wall rigidity and fixation for effective respiratory effort, to prevent flail segments and reduce paradoxical movements, and prevent herniation. Small defects (those involving fewer than three ribs) can usually be covered primarily with muscle and skin; those greater than 5 cm often require chest wall reconstruction, as a large flail segment would otherwise result. Posterior defects of up to 10 cm in diameter can be tolerated as long as the scapula remains to provide stability. Generally, resection of ribs 1–4 posteriorly is well-tolerated, but if resection also involves the fifth and sixth ribs, additional support is necessary to prevent the scapula from becoming caught below the lower ribs. Resections that include the lower ribs can be reconstructed by reapproximating the diaphragm to the lowest remaining rib. This transforms a thoracic defect into an abdominal defect, which has less physiological consequences. However, this technique cannot be used if the resection extends above the fifth rib. Defects involving the sternum should be reconstructed to protect underlying structures and to prevent the paradoxical motion that occurs with the removal of the anterior costal attachments. Defects involving mid-thoracic segments can be reconstructed with a rib transposition, by disinserting the anterior portion of the rib below the defect from the sternum and fixing it back to the sternum or the remaining extremity of a resected rib in the middle of the defect. Prosthetic materials should be avoided whenever possible to decrease the risks of infection and complications related to radiation therapy. Several materials and techniques have been used to reconstruct large chest wall defects, including fascia lata, omental transplants, contralateral rib grafts, assorted muscle flaps, and prosthesis, including Gore-tex and other non-absorbable materials [87]. The major deterrence to the use of these prosthetic materials in the young infant or growing child is that they do not expand as the child grows and may result in more severe scoliosis than occurs if the defect is closed with living tissue. Prosthetic materials provide a rigid base for reconstructing chest wall defects, but the overlying soft tissue must also be replaced. The pectoralis major, latissimus dorsi, and rectus abdominus myocutaneous flaps and the greater omentum are all available for use [87].

21.3 Surgical Approaches in Pediatric Thoracic Tumors

21.3.1 Posterolateral Thoracotomy

The patient is placed in a full lateral decubitus position with appropriate pressure point padding. The skin incision is started at the level of the anterior axillary line over the fifth intercostal space. It is curved around the tip of the scapula and continued posteriorly along a line between the medial aspect of the scapula and the spine. It is carried upward to the level of T4. Anteriorly, the skin incision follows the rib outline (Fig. 21.7a). If an additional posterior extension is required, the anterior portion of the trapezius and rhomboid muscles can be divided. If an additional anterior extension is required, the skin incision is extended to the lateral edge of the sternum, and the serratus anterior and pectoralis major muscles are divided. The mammary vessels

are dissected and ligated in case a partial sternotomy is needed [88–90]. The thorax is then entered either in the intercostal space or with a partial rib resection with preservation of the periosteum, which is split on the midline. Dissection then begins with mobilization of the thymus and identification of the phrenic, vagus, and recurrent laryngeal nerves. The tumor is dissected piecemeal, in a cranial direction, and major vascular structures are controlled proximally and distally. For teratomas, an attempt to remove the whole tumor and prevent spillage of cells is optimal, although not always possible. When the thoracic duct can be identified, it is isolated, tied, and ligated. Meticulous dissection continues with frequent use of neural monitoring, and marginal biopsies are taken after tumor extraction. Once the tumor is completely removed and lymph nodes have been sampled (if necessary), a chest tube is placed one or two intercostal spaces below or above the thoracotomy (Fig. 21.7b). The ribs involved in the thoracotomy are approximated with pericostal interrupted absorbable sutures. If the rib was partially resected, the periosteum is now sutured on the midline to facilitate rib regrowth.

21.3.2 Thoracoscopy

Thoracoscopic surgery in pediatric oncology remains an evolving field that has grown over the past 30 years. Surgical intervention remains a standard principle underlying the multidisciplinary treatment of many childhood cancers, and the integration of minimally invasive surgery (MIS), including thoracoscopic approaches, requires validation for the efficacy of these surgical techniques and to expand the indications of MIS for the treatment of pediatric cancer. To date, the paucity of outcome data has limited the ability to create guidelines for the use of MIS in pediatric oncology. Many children with pulmonary or mediastinal masses may initially require

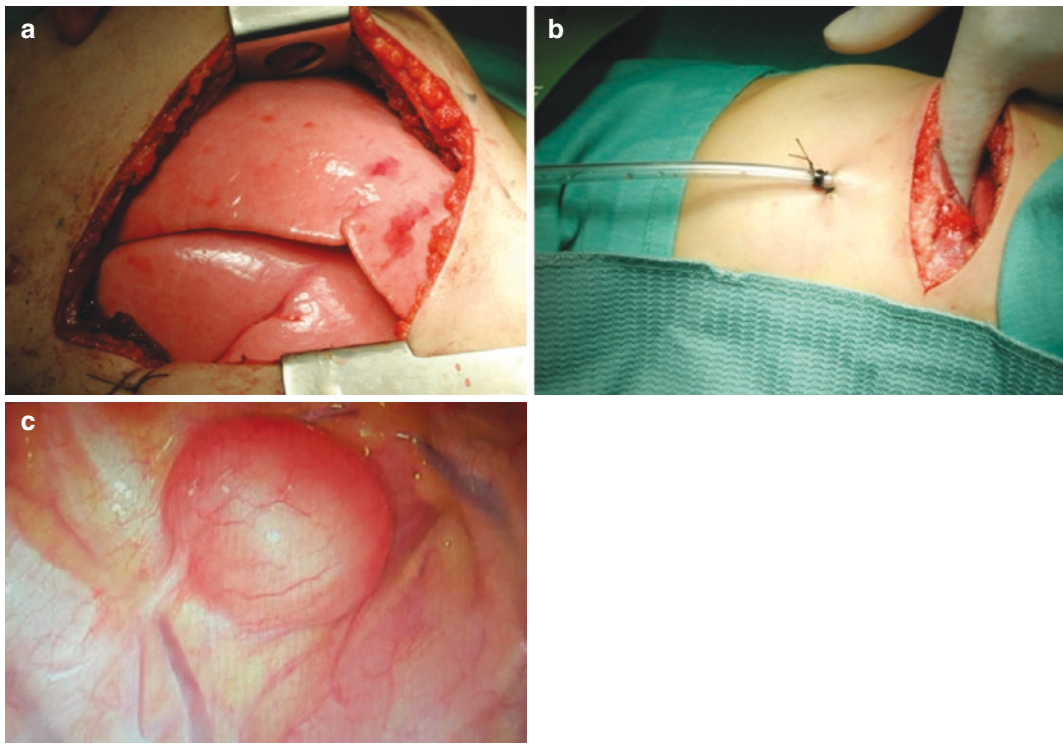

Fig. 21.7 (**a** and **b**) Posterior thoracotomy and chest drain insertion. (**c**) Thoracoscopic resection of a localized thoracic neuroblastoma.

tissue for pathologic diagnosis and in some circumstances tumor resection. Although percutaneous biopsies may be performed with the assistance of image-guided technology, situations remain in which a surgical biopsy is required either via the thoracoscopic or the open surgical technique [91]. A thoracoscopic approach is to be considered to limit long-term sequelae such as winged scapula and scoliosis in this special population. Pediatric surgeons have used thoracoscopy to diagnose and resect benign, malignant, or metastatic intrathoracic tumors [92]. However, tumor extirpation remains controversial and continues to be limited (Fig. 21.7c).

Theoretical advantages of using thoracoscopy include access to a wide area through limited incisions, better visualization of thoracic and mediastinal structures, and magnification of the local anatomy. Additionally, the use of thoracoscopy has led to a decreased intraoperative blood loss, decreased postoperative pain, reduced hospital length of stay, fewer chest tubes required and/or earlier removal, improved cosmetic result, faster return to normal activity, and reduced pulmonary adhesions [93–102].

Factors limiting the use of thoracoscopy in children with cancer are related to the surgeon, patient, pathology, and technology. Pediatric surgeons' experience with advanced thoracoscopic techniques may be limited. Although the ability to gain thoracoscopic experience has increased over time, the relatively low volume of pediatric oncologic cases encountered by general pediatric surgeons can negatively impact their decisions or confidence to use a thoracoscopic approach. Single-lung ventilation with double-lumen endotracheal tubes is unavailable for the smallest of patients, and, alternatively, bronchial blockers require highly skilled anesthesiologists for the fragile airway of small children [103]. Although thoracoscopy is feasible using only positive pressure carbon dioxide insufflation without single-lung ventilation, the resulting lung collapse is often suboptimal, thus hampering visualization of pulmonary nodules, decrease working space in the thorax, and increasing the risk of lung injury. The small working space within the thoracic cavity or mediastinum, the patient's ability to tolerate single-lung ventilation, and hemodynamic effects caused by pressure generated by pneumothorax are competing factors that make every case uniquely different.

Large masses can potentially impede safe accessibility and specimen delivery and contribute to the potential risk of intraoperative tumor spillage and port-site recurrence [104, 105]. Deep or subcentimeter pulmonary lesions are difficult to visualize, and because the tactile ability is lost in thoracoscopy, these pulmonary lesions may be missed [106]. Adhesions due to prior thoracotomy may limit the ability for a thoracoscopic approach. This is especially relevant in scenarios where multiple serial thoracic surgeries are expected over the course of the disease, such as with serial pulmonary metastasectomies for recurrent metastatic osteosarcoma.

Complications related to thoracoscopy are not different from those encountered in traditional open surgery. A direct comparison of percentages of complications in these different approaches is frequently biased by selection criteria, which generally favor the use of thoracoscopy in "easier" cases. [93, 94, 96, 105, 107–109]. Recurrence at the chest tube site has been reported after thoracoscopic resection of pulmonary metastasis from osteosarcoma [105], although this is extremely rare.

Inadequate equipment, insufficient training, and experience are considered contraindications to performing advanced thoracoscopy. Relative contraindications can be anatomical, such as difficult thoracic access due to large tumor size with consequently increased potential for tumor rupture or spill, and physiologic, such as abnormalities in cardiac output, difficulty tolerating single-lung ventilation or thoracic carbon dioxide insufflation, and coagulopathy [98].

With ultra-advanced technologies, rapidly improving thoracoscopic training, and adherence to the fundamental oncologic principles in surgical technique, pediatric surgeons from across the world can selectively customize treatments for thoracic and mediastinal tumors in neonates, infants, and children. However, significant oncologic concern remains whether malignant tumors can be safely removed in these

children, given the risk of potential iatrogenic tumor cell dissemination and metastasis. Appropriate patient selection and correct surgical indications for advanced surgical procedures in children with cancer are necessary to minimize the risk of surgical complications.

21.3.2.1 Surgeon and Patient

The safety threshold and the patient selection are important for consideration of any thoracoscopic approach. The surgeon's experience, patient size, detail regarding the potential pathology, location, and proximity to vital structures all impact the final decision of whether or not to pursue this minimally invasive approach.

21.3.2.2 Anesthesia

Thoracoscopic surgery requires the ability to create enough working space within the hemithorax to safely visualize and perform the operative procedure. Impediments that lead to difficulty with anesthesia in infants and young children include one-lung ventilation (OLV), carbon dioxide insufflation, hypothermia, and the effect of lateral decubitus positioning [110–114]. The smaller tracheal and bronchial diameters in children and infants may prohibit the use of double-lumen tubes or bronchial blockers because there is a lack of double-lumen tubes and commercially available bronchial blockers. OLV currently remains a technically difficult and demanding task on behalf of the anesthesia team.

Key safety considerations in the decision to adopt a thoracoscopic surgical approach are heavily influenced by the risk of cardiopulmonary collapse under anesthesia. In children with anterior mediastinal masses due to Hodgkin's or non-Hodgkin's lymphoma or less commonly neuroblastoma or germ cell tumors, the pros and cons of proceeding with an anesthetic need to be considered, especially in the presence of airway compression. General anesthesia should be avoided in patients with tracheal cross-sectional area or peak inspiratory flow rate less than 50% of predicted for age and sex, and those with less respiratory compromise can generally safely undergo general anesthesia [115]. Thoracic epidural anesthesia or bilevel positive airway pressure management has been used in children for open biopsies of anterior mediastinal masses [116, 117].

21.3.2.3 Localization and Biopsy

Thoracoscopic biopsy of intrathoracic lesions has been effectively used for mediastinal masses, most commonly neuroblastoma and lymphoma, and for pulmonary masses that are usually metastatic lesions or infiltrates. Approaches for localization include image-guided hook wire, methylene blue injection, and/or the utilization of endoscopic ultrasound [91].

Although these various preoperative localization techniques serve as adjunctive tools, several case series have been reported using thoracoscopic biopsy without preoperative localization with excellent results [118, 119]. Conversion to open thoracotomy ranged from 0% to 30% and was primarily due to limited visibility, adhesion, bleeding, decreased intraoperative oxygen saturations, and hypercarbia. Therefore, thoracoscopy was largely successful, and some patients were able to begin adjuvant therapy earlier [91].

21.3.2.4 Future Developments

Single-incision surgery allows chest surgery to be performed through a single access site that admits multiple working instruments. Experiences with pediatric single-incision thoracoscopic surgery for tumors are extremely rare [120].

Robotic surgery eliminates tremors and allows three-dimensional vision with a magnified view and the use of articulated instrumentation [103]. Mediastinal masses are proposed as “the golden indication” for robotic resection, and successful resection has been reported of malignant tumors such as neuroblastoma and mediastinal germ cell tumor, tumors of intermediate malignant potential, including ganglioneuroblastoma and lipoblastoma, and benign tumors, including ganglioneuromas and mature teratomas [103, 121]. Limitations such as robot costs compared with standard thoracoscopy are thought to be the single most limiting factor in the use of this technology. Additional factors are the limited hemithorax space in patients less than 2.5 kg, instrumentation size and availability, and learning curve [121].

21.3.3 Cervicothoracic Tumors

High thoracic tumors and tumors of the cervicothoracic junction are often not amenable to complete resection by either an isolated unilateral cervical or thoracic approach. Nonetheless, adequate surgical exposure of these tumors is essential to prevent injury to nearby nerves (brachial plexus, phrenic, vagus, recurrent laryngeal, and spinal accessory) and vascular structures (carotid, subclavian, and vertebral arteries, the thyrocervical trunk, and the subclavian and jugular veins), while assuring complete resection. Large mediastinal tumors that require access to both hemithoraces also present a challenge to complete resection with low postoperative morbidity. Series regarding pediatric bilateral anterior thoracotomy ("clamshell" approach) are found most often in the cardiothoracic literature. Isolated case reports have described excellent exposure for resection cervicothoracic junction tumors using a combined supraclavicular incision sternotomy-anterior thoracotomy ("trap-door" approach).

21.3.3.1 Transmanubrial Approach

The technique was described initially by Grunenwald and Spaggiari in 1997 [122]. The patient is placed in dorsal decubitus, with a roll placed under the shoulder. An L-shaped skin incision is made, the upper line corresponding to the anterior part of the sternomastoid muscle as far as the angle of manubrium and prolonged in an anterior thoracotomy at the level of the second rib. The sternal manubrium is exposed after dissecting the sternomastoid muscle (from the anterior part to the internal jugular vein), sparing the major pectoral muscles. The originality of this technique lies in the division of the superior lateral part of the manubrium and after the cartilage section of the first rib, with an L-shaped incision. After cutting the insertion of the anterior scalene muscle, an anterior flap is retracted progressively, preserving the sternoclavicular articulation and the insertion of the sternomastoid muscle, and offering a perfect plane of dissection for the subclavian vessels. Tumor dissection then begins, starting with the internal jugular vein and its junction with the brachiocephalic vein (Pirogoff confluence). Step by step, all the vascular and nervous structures are exposed (subclavian and jugular vein to the brachiocephalic vein, subclavian artery, phrenic and vagus nerve, and control of the carotid artery). In the posterior plane, dissection exposes the anterior part of the vertebral bodies from C3 to T4. Moreover, this dissection facilitates the removal of extradural intraspinal involvement and pleural extension. Ligation of the thoracic duct can be performed easily for left-sided tumors. Reconstruction of the manubrium is performed with resorbable sutures [88].

21.3.3.2 Trap-door Incision

The patient is placed in the dorsal recumbent position with a roll beneath the shoulders, the arm ipsilateral to the lesion outstretched, and the contralateral arm tucked at the side. General anesthesia is induced, using either a double-lumen endotracheal tube or a single lumen endotracheal tube with a bronchial blocker for intubation. The head is then rotated 30–45° away from the tumor. The patient is prepped from the ear to the umbilicus and a clear head and neck drape is used. A transverse incision is begun superior to the clavicle with a parallel course, or along the anterior border of the sternocleidomastoid with a descending course, to the mid-portion of the suprasternal notch, continued downward through the midline sternum to the fifth interspace, then laterally through the fifth interspace to the anterior-axillary line (Fig. 21.8). The pectoralis is divided close to its point of insertion, and the intercostal muscles are divided at the fifth interspace. The pleural space is entered and the internal mammary vessels are isolated, ligated, and divided. The retrosternal space is bluntly dissected, and a sternal saw is used to divide the sternum to the level of the fifth interspace, then laterally to the thoracotomy. Bleeding from the edge of the sternum is treated with bone wax. The sternal and a portion of the clavicular head of the sternocleidomastoid are divided close to their points of origin and marked with sutures for later approximation. The strap muscles are similarly divided. A retractor is then placed between the cut edges of the sternum allowing excellent

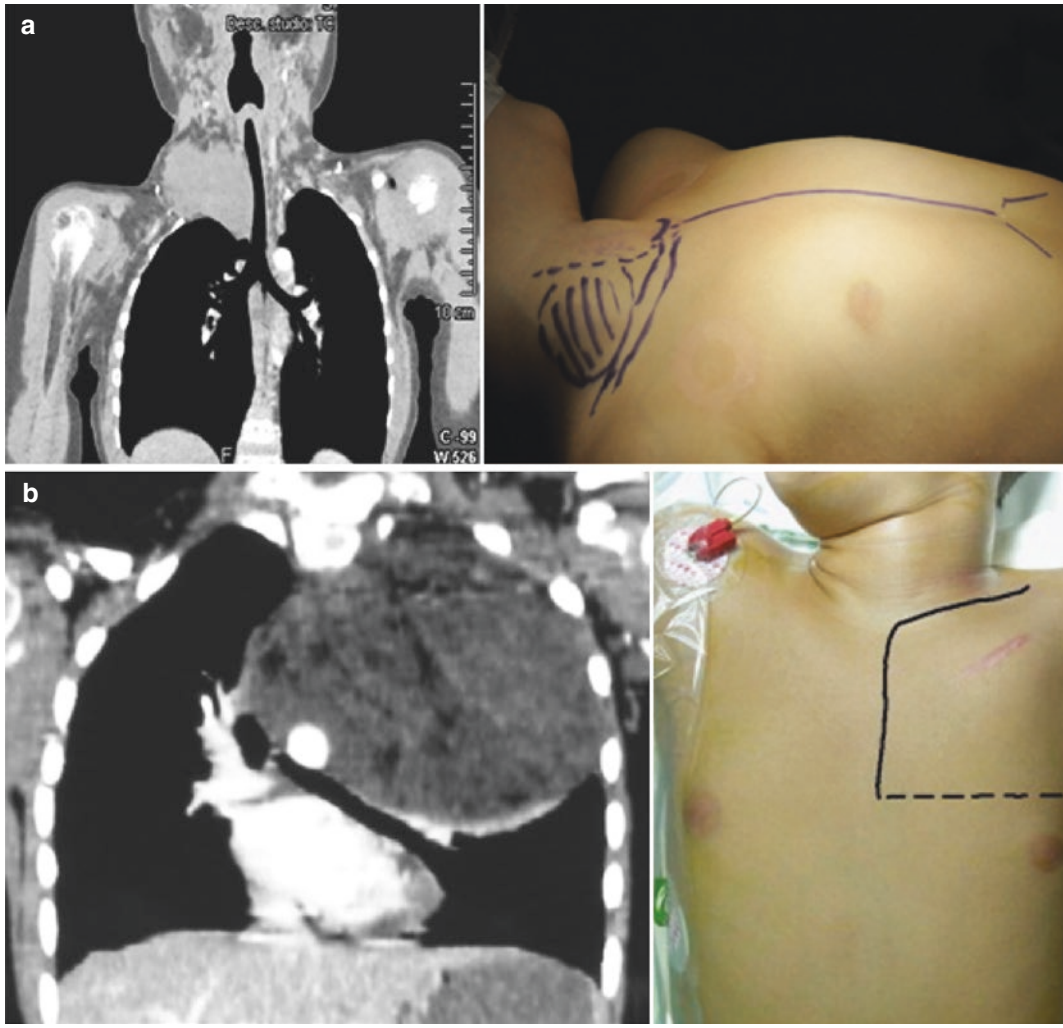

Fig. 21.8 (**a**) Right schwannoma tumor located at the right thoracic inlet, involving major cervical vessels and nerves. Anterior cervical transsternal approach was adopted. (**b**) Rhabdomyosarcoma located at the posterosuperior left mediastinum, determining compression and right-anterior displacement of the esophagus and trachea. The aorta is compressed and shifted medially, with slight anterior dislocation of left carotid and left subclavian artery: the left pulmonary artery and left principal bronchus appear compressed and inferiorly displaced; superiorly, the mass arrives in proximity to the left thyroid lobe. Trap-door approach was adopted. (with permission from De Corti F et al. The surgical approach for cervicothoracic masses in children. J Pediatr Surg.2012 Sep;47(9):1662-8)

exposure. At the end of the dissection, the sternum is reapproximated with 3–4 sternal wires or nonabsorbable sutures in small patients. The thoracotomy is closed as described above. The lungs are then inflated under direct vision, and the pericostal sutures and sternal wires are secured. The mobilized edges of the pectoralis flaps are closed over the sternal wires. Attention is then directed to the neck where the sternal and clavicular heads of the sternocleidomastoid muscle are reapproximated with the figure of eight sutures of heavy absorbable suture [90].

21.3.3.3 Sternotomy

The procedure consists of an anterior cervical transsternal approach as described by Ladas et al [123] and also previously adopted by Grosfeld et al [124]. The patient is placed in a

supine position, with the head extended and rotated contralaterally to the mass. The incision extends from the level of the thyroid cartilage downward along the anterior margin of the sternocleidomastoid muscle onto the manubrium and the upper sternum (Fig. 21.8). If required—in case of malignant infiltrating tumors—the incision may be prolonged caudally to perform a complete sternotomy. The clavicle is not resected. In instances of large-sized tumors, the sternocleidomastoid muscle may be divided to allow better exposure of the surgical field and reattached at the end of the operation. This approach offers a wide exposure of the cervical neurovascular structures, subclavian vessels, and brachial plexus. Vessels are identified and progressively isolated to guarantee immediate vascular control in case of bleeding during dissection of the mass. The tumor is progressively freed from the surrounding structures, making sure to preserve the roots of the brachial plexus (a nerve stimulator may be used) as much as possible. Once the tumor is removed, a laminar drain is placed in the surgical field along with a suction drain in the anterior mediastinum. A chest drain is not necessary unless the pleura is breached.

21.3.4 Thoraco-abdominal Tumors

21.3.4.1 Thoraco-phrenolaparotomy

The child is positioned on the homologous oblique lateral decubitus with the arm lifted and bent over the head, avoiding any outstretched position to reduce the risk of brachial plexus injuries. Then, the surgeon identifies the 10th rib and marks the skin. A single skin incision is made following the 10th rib, starting posteriorly from the inferior margin of the scapula proceeding obliquely downward on the lateral margin of the rectus abdominis muscle beyond the umbilical transverse line. The rib is exposed and partially resected with preservation of the periosteum as described above. Then, the parietal pleura is incised to get access into the chest cavity. This leads to the wide exposure of the lung, diaphragm, and thoracic parts of the tumor. Selective lung ventilation is not generally required.

Laparotomy is performed following the direction of the lateral margin of the rectus abdominal muscle. Blunt dissection of the peritoneum from the diaphragm proceeds till touching the abdominal part of the tumor.

The diaphragm is incised along the posterior peripheral margin close to its insertion on the lateral chest wall to avoid phrenic nerve lesions.

Once thoracotomy, laparotomy, and diaphragmatic incision are performed, intrathoracic and retroperitoneal spaces are both accessible and tumor complete resection can proceed following the usual steps.

A chest tube and a retroperitoneal suction drain are placed once the tumor is completely removed. The diaphragm is closed using interrupted non-absorbable sutures.

21.3.5 Bilateral Thoracic Tumors

21.3.5.1 Clamshell Incision

The patient is placed in the dorsal recumbent position with a roll behind the midportion of the chest. The arms are abducted to 90° at the shoulder and elbow. General anesthesia is induced with a double-lumen or single-lumen endotracheal tube capable of lung isolation, and the patient is prepped from the chin to the umbilicus and transversely to the bilateral posterior axillary lines. An anterior curvilinear incision is made along the fifth interspace bilaterally from each anterior-axillary line, connecting at the midline. The pleural space is entered and the mammary vessels are isolated, ligated, and divided. The retrosternal space is then bluntly dissected, and the sternum is divided transversely with a sternal saw. A retractor is placed, allowing for exposure of both pleural cavities, from the pulmonary hilum to the posterior aspect of the diaphragm. When the tumor dissection is complete and hemostasis is assured, bilateral chest tubes are placed and the sternum is either approximated with wires. Pericostal sutures are used to approximate the ribs.

21.4 Complications

21.4.1 Cardiopulmonary Complications

21.4.1.1 Atelectasis

Intraoperatively, adequate inflation of the lungs by positive pressure ventilation should be assured by looking at the lung at the time of closure or completion of thoracoscopy. After the operation, pain relief is critical to allowing the full opening of the lung. While some degree of atelectasis is a normal postoperative finding, it responds well to incentive spirometry, flutter valve, and other measures for a pulmonary toilet. How frequently atelectasis leads to pneumonia is unclear but not often. Family members can encourage the patient with these measures, and this helps them to realistically feel they are contributing to recovery.

21.4.1.2 Pneumonia

Postoperative pneumonia in children occurs in several settings, generally following atelectasis. Its incidence ranges between 9% and 21% according to different series. Gram-negative bacilli generally predominate, causing 86% of cases of pneumonia. Fungi caused 7%, and the remainder is related to gram-positive cocci (7%). With increasing antibiotic resistance recently reported in most centers, local susceptibility patterns must be followed.

21.4.1.3 Respiratory Distress Syndrome (RDS)

Respiratory distress syndrome (RDS) arises in children from the same pathophysiologic processes as in adults. Pulmonary edema occurring as a result of oncotic and hydrostatic pressure differences leads to fluid in the alveolar spaces. RDS in children is often complicated by infection of the edematous lung and may require prolonged ventilatory support and tracheostomy. Management remains controversial.

21.4.2 Complications of Chest Incision

Posterolateral thoracotomy complications noted in a series of 49 children [125] were: scoliosis, 31%; elevation of the shoulder 61%; winged scapula 77%; asymmetry of the thoracic wall due to atrophy of the serratus anterior 14%; deformity of the thoracic cage 18%; and asymmetry of the nipples 63%. A greater incidence of denervation problems was noted with more cephalad incisions. Most of the abnormalities were not functionally significant but caused the authors to recommend that incisions should be as low as possible, and should be performed after the first year of life if possible.

Median sternotomy in childhood has been followed by scoliosis in 34%. Median sternotomy is sometimes complicated by mediastinitis or sternal wound infections.

Thoracoscopy or VATS operations should minimize the incidence of neurologic and chest wall complications that confound surgeons obliged to use a posterolateral thoracotomy. However, the approach is not without difficulties. Preparations should be made for rapid thoracotomy in case of unexpected massive hemorrhage.

Scoliosis is a well-established complication of thoracotomy and/or chest wall resection. The severity of the curve is directly related to the number of ribs resected. Resection of the posterior segment of ribs produces more scoliosis than resection of the anterior segments. Similarly, resection of lower ribs produces a greater curve than resection of upper ribs [126]. Radiation can also affect the growth of the hemivertebrae on the radiated side. Scoliosis is often progressive until the child reaches full stature and therefore requires long-term follow-up. For these reasons, several authors recommend techniques sparing the serratus anterior and latissimus dorsi.

21.4.3 Complications of Pulmonary and Bronchial Resection

21.4.3.1 Pneumothorax

Pneumothorax or prolonged air leak from a thoracostomy tube following thoracic surgery may be a result of air leaking from the chest drainage device, air entering the chest along the chest tube as it passes through the chest wall, or leak from the lung. Air leak from a bronchial stump leak is more troublesome. This complication is

sufficiently infrequent in children that an incidence is hard to obtain. Air leak is often associated with debility, poor nutrition, infection, or malignancy, and reoperation on a high-risk patient.

21.4.3.2 Restrictive Pulmonary Function

Residual pulmonary function depends on the amount of lung parenchymal resection in case of pulmonary tumors and/or on the entity of chest wall resection and consequent scoliosis. The forced vital capacity (FVC), forced expiratory volume, and functional residual capacities (FRC) studied from 1 month to 10 years after surgery demonstrates minimal early reduction in the FRC and FVC. Progressive worsening over time may be noted, with all patients eventually demonstrating a certain degree of pulmonary restrictive disease.

21.4.4 Complications Involving the Pleural Space

21.4.4.1 Pleural Effusion

Pleural effusion following thoracotomy is more commonly an expected outcome of the operation rather than a complication and is usually managed adequately by placing chest drains at the time of surgery. Reaccumulation after drain removal might indicate premature removal but might also signal the development of pneumonia with effusion or hemorrhage.

21.4.5 Complications of Mediastinal Surgery

21.4.5.1 Chylothorax

Chylothorax occurs in a variety of mediastinal operations in 1–4% of cases. Chylothorax is initially managed by placing and leaving a chest tube. The median duration of drainage is generally 15 days. The great majority responds to treatment with dietary modification and/or octreotide. Surgical ligation of the thoracic duct was reported to decrease but not eliminate drainage. Recent reviews in the critical care medicine literature note that there is no consensus about the optimal route of administration, dose, duration of therapy, or strategy for discontinuation of therapy. Thoracic duct ligation has been successfully performed thoracoscopically [127].

21.4.5.2 Diaphragmatic Paralysis

Diaphragmatic paralysis can result from phrenic nerve injury by dissection, clamp, electrocautery, or ice used for cardioplegia. Phrenic nerve injury is a serious complication. Its frequency was reported to be 1.5%. Half of the patients may require plication of the diaphragm. Video-assisted plication can be performed generally through an abdominal approach [128].

21.4.5.3 Spinal Ischemia

Posterior mediastinal tumors may extend into the intervertebral foramina and may potentially compress the spinal cord. Moreover, resection of inferior posterior mediastinal tumors carries the possibility of injury to the artery of Adamkiewicz (AKA), typically located at the level of T9–T12. Disruption of the AKA may lead to anterior spinal cord ischemia and subsequent paraparesis or paraplegia. Some authors suggest to routinely perform a spinal angiography for all posterior mediastinal tumors with intraforaminal involvement located between the levels of T5–L1 in order to visualize the AKA for preoperative surgical planning [129].

21.4.5.4 Horner Syndrome

The classic triad of Horner syndrome, consisting of ipsilateral miosis, mild upper eyelid ptosis, and facial anhidrosis, is caused by interruption of at least one of the three neurons in the oculosympathetic pathway. Neuroblastoma is the most common neoplasm presenting with Horner syndrome and, indeed, an isolated Horner syndrome is the first presenting symptom of neuroblastoma in 2% of cases. Horner syndrome may obviously appear following resection of a tumor involving and/or located at the stellate ganglion [130].

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