25 Pneumothorax and Pneumomediastinum

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25.1 Pneumothorax (PNX)

PNX is a collection of air in the pleural cavity which leads to crushing of the lung and its consequent collapse [1]. Lung collapse may be partial or total and in some hypertensive forms it can also lead to the shift of the mediastinum towards the opposite hemithorax. PNX can be classified into four main groups [2]:

- spontaneous: with no apparent cause;
- secondary: the result of an underlying disease that may lead to the rupture of one or more pulmonary alveoli;
- iatrogenic: as a consequence of medical or resuscitation maneuvers that may cause air leakage from the lung;
- traumatic: caused by direct trauma to the open or closed chest.

A further distinction is based on the possible communication between the chest cavity and the external environment. It is of great importance, especially in the case of post-traumatic or iatrogenic PNX, and three forms can be recognized: closed, open or valve.

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25.1.1 Etiology and Pathogenesis

Spontaneous PNX (i.e., with no obvious underlying cause) is relatively rare in children [2]. It has a bimodal distribution by age with two peaks: one in the neonatal stage and the other during late adolescence [3]. The newborn may manifest PNX in three conditions.

- The first condition is spontaneous PNX. Spontaneous PNX occurs soon after birth (1% of births) due to the high transpulmonary pressure exerted during the first breaths. In addition, it is symptomatic in just 10% of cases (0.1% of newborns). It is nearly always normotensive and tends to resolve spontaneously (in the case of persistence or an increased need for drainage) [1, 2].
- The second condition is PNX during respiratory distress. Uneven alveolar ventilation, air trapping and lung hyperinflation lead to rupture of the alveoli with air accumulation inside the pulmonary interstices first and then inside the pleural cavity. It tends to restock and it is often hypertensive and drained (during mechanical ventilation PNX should always be drained).
- The third condition is PNX after attempts at central venous catheter (CVC) placement beneath the clavicle. In this scenario, puncture of the lung parenchyma occurs.

In the adolescent, spontaneous PNX is instead related to growth. The subjects most affected are mainly lean and apparently

M. Lima (ed.), *Pediatric Thoracic Surgery*,
DOI: 10.1007/978-88-470-5202-4_25,

healthy. In this group, development has led to a rapid vertical growth of the chest as opposed to horizontal growth [1–3]. This discrepancy is responsible for an increase in the negative pressure at the apex of the lung that leads to the formation of subpleural bubbles (also air–fluid) which, once broken, will cause PNX.

25.1.2 Clinical Features

Air flow inside and outside the lungs (i.e., ventilation) is due to pressure gradients between the alveoli and the external or atmospheric air. Inspiration occurs if the atmospheric pressure is greater than alveolar pressure, causing a pressure gradient that moves the air inside the alveoli. Exhalation occurs if the pressure in the alveoli is greater than the atmospheric pressure, and this is considered to be a passive process because it does not require muscle contraction.

PNX leads to partial or total collapse of the lung parenchyma. If the lung collapses completely, intrapleural pressure is balanced with that of the atmosphere, and this pressure balance prevents the air entering the lungs *via* the airways from moving freely. This in turn disturbs the capacity of alveolar gas exchange because, as mentioned above, normal breathing occurs only if atmospheric and intrapulmonary pressures are different. This then results in breathing difficulties, which are proportional to the degree of PNX up to the point that it could turn into acute respiratory failure, so that the clinical manifestations are those of different degrees of dyspnea.

25.1.3 Diagnosis

PNX is diagnosed by chest radiography (Fig. 25.1). With large pneumothoraces, radiographic identification is easy. In many cases there is associated medial herniation of the pleural space across the anterior mediastinum, a finding that is especially useful in the identification of anterior PNX. In infants and toddlers, because they are lying flat, the free air collection is anterior to the lung. Confirmation of PNX can be obtained with lateral views.

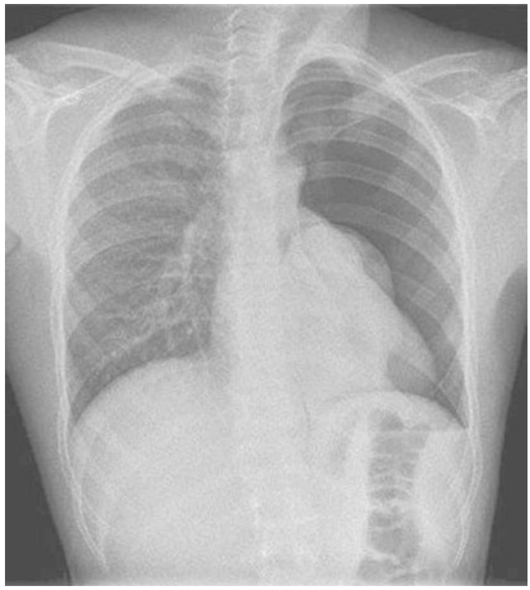

Fig. 25.1 Left massive PNX

Lesser-volume PNX is more difficult to identify. Knowledge of all areas of potential air collection is extremely helpful if a free lateral lung edge is not visualized. If a PNX collects medially the findings must be differentiated from pneumomediastinum (PM) or pneumopericardium (PE).

Patients in the scholar age with spontaneous and recurrent PNX must be evaluated with computed tomography (CT) (Fig. 25.2) to exclude a cystic lesion of the lung. Most patients with large cysts are usually detected in the prenatal age or present with respiratory distress in the neonatal period or shortly after. However, those with smaller lesions may present later because symptoms may take years to develop.

25.1.4 Management

Chest drainage is designed to restore ideal conditions in the pleural space by removing

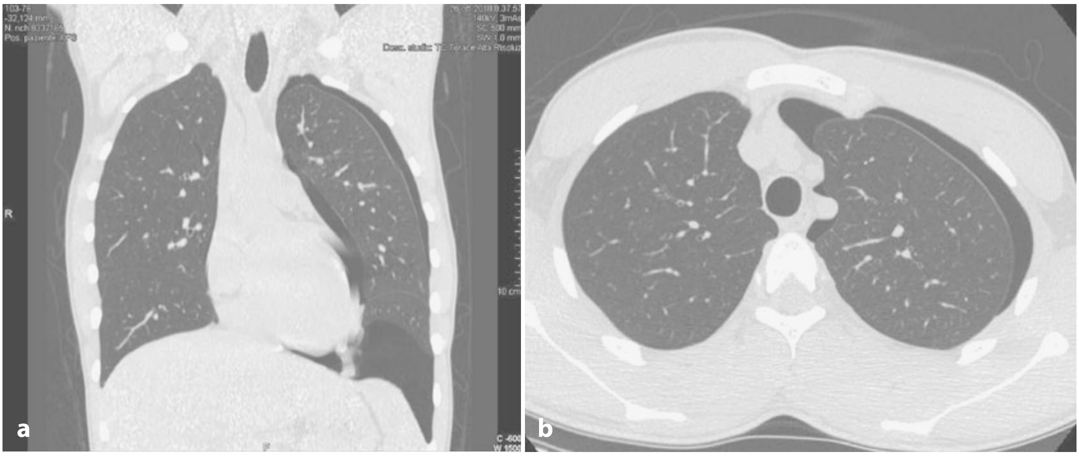

Fig. 25.2 Left PNX with thickening of the dorsal thoracic pleura of the inferior lobe. No pulmonary parenchimal lesions. At the apex of both lungs parenchimal air bullae can be observed (two in the right lung and one in the left one)

the causes of breathing difficulties (PNX, PE). The equipment for chest drainage is:

- drain tube with trocar for the insertion of different sizes (Fig. 25.3);
- Pleur-Evac®-type intake system;
- drainage and Pleur-Evac connection set;
- number 11 disposable scalpel blade;
- needle-holder, Klemmer-type forceps, sterile surgical forceps and scissors;
- sterile drape;
- 3-0 and 4-0 nylon sutures.

The type and location of the drainage tube will vary depending on the material (air or liquid) that needs to be drained from the pleural space. The air tends to collect upwards, the liquid downwards, so the drainage tube for a PNX should be directed towards the apex of the chest cavity and anterior part of the lung. *Vice versa*, for drainage of liquid collections, the drainage tube is directed to the diaphragm and the back of the lung. For children aged <1 year, who are predominantly in a supine position, directing the drainage tube anterior to the lung for the PNX and to the posterior in PE cases is sufficient.

If the collection inside the cavity is hematic or serous, the drainage tube must be larger to prevent the tube becoming clogged up by clots. If only air must be drained then a smaller-diameter drain can be used.

Fig. 25.3 Drain tubes with endoluminal trocar of different sizes. From [13]

25.1.4.1 PNX drainage

Patients must be distinguished according to their age and PNX severity. The first measure to be taken in case of a hypertensive PNX that causes an acute respiratory crisis is to remove the air from the chest as quickly as possible [2]. To achieve this it should suffice to insert a percutaneous type-18 Abbocath Ch venous catheter into the chest or a large needle attached to a three-way stopcock and two 50-cm^3 syringes with which air will be drawn out repeatedly. During this extemporaneous procedure, conducted in an emergency, the nursing staff can prepare the equipment for the chest tube. Once all the equipment is ready, the needle will be removed, the patient will be examined and chest raiography will be done. After PNX has recovered a drainage tube using standard methods will be placed as described below.

The pleural drain can be placed along the mid-clavicular line in the second or third intercostal space [2], or in the axillary region in the third or fourth intercostal space along the mid- or rear axillary line. The choice of an intercostal space lower than the fifth intercostal space should be supported only by positioning *via* guided ultrasound or treatment to prevent injuries to the diaphragm or viscera immediately below (liver and spleen first and foremost). The choice depends on: patient age; the personal preferences of the operator; esthetic considerations (the axillary line is covered and recommended, especially for female patients); material to be drained (air alone, or air combined with effusion); and drainage management. Sometimes, if the collected material is mixed (air–liquid) it may be necessary to place two different drainage tubes.

Normally, if possible, the tube is placed along the anterior axillary line at the fourth intercostal space [2]. The skin incision for the entry hole can also be made in the intercostal space below, taking care to insert the drain through the chest wall in the upper space. This creates an inclined passage that helps to reduce the risk of accidental removal of the tube, as well as reducing other risks related to the entry of external air from around the drainage tube.

After local anesthesia, a skin incision is made ≈1–2 cm in the middle of the lower rib of the chosen space. Once the costal level is reached, the Klemmer curved forceps are introduced until the top edge of the rib is reached. Then, by blunt dissection through the muscle fibers, the pleural level is reached. After having created a space with the forceps, we insert the tube with a spindle, and by thrusting (keeping the index finger of the hand holding the drain against the chest wall to avoid sudden penetration of the chest with the spindle for a distance greater than its tip) (Fig. 25.4) we can penetrate the chest. At this point, the characteristic noise of air entering the chest

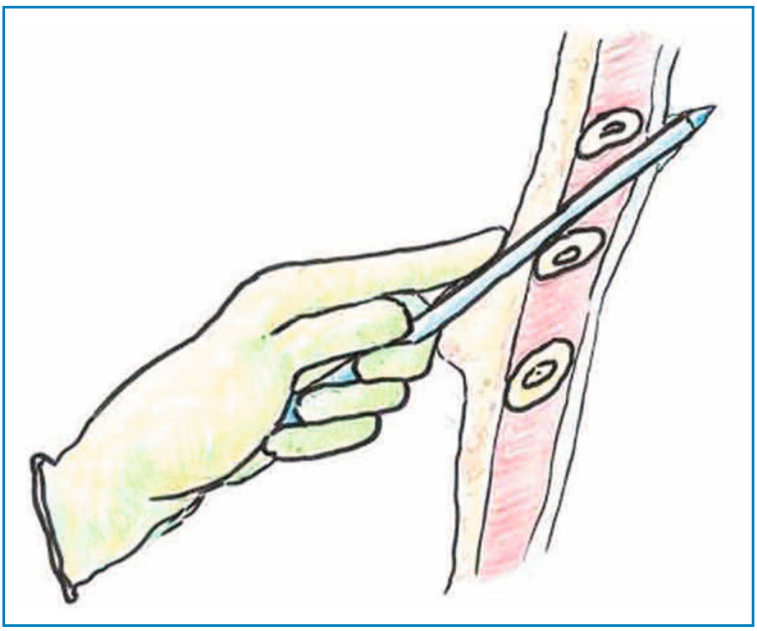

Fig. 25.4 Correct and safe way to hold the trocar. Note the index that reduces the risk of entering too deep with the sharp tip into the thoracic cavity provoking injuries to the lung, the heart or great vessels. From [13]

can be heard. Then the tube is directed up or from the back (depending on the drainage purpose). The rubber part is advanced up until the sign that had been previously chosen, taking into consideration the size of the child and the length of the drain; it is better to exceed slightly with the introduction of the drain and, if it is the case, to retract it after the RX control. This way a correct positioning is gained more easily. If too a little part is inserted, one has to insert the drain more after the X-ray, some minutes later, when the external part is no longer sterile.

Once the tube is placed and the spindle extracted, the junction is connected to the water valve and the wound is sutured with a non-absorbable suture so that it is closely adherent to the tube diameter. By means of a second non-absorbable stitch we make sure that the tube is attached firmly to the skin to avoid accidental removal ("spartan suture"). With a non-absorbable third stitch we place a "tobacco pouch" suture with which we close the drainage access hole definitively once the drain has been removed.

Once this has been done the wound is medicated, making sure to patch the tube to the skin and carry out chest radiography to check the position of the drain. Drains are made of polyvinyl chloride (which is radio-transparent) or silicone (which is radio-opaque), usually with a radiologically visible filament) (Fig. 25.5).

During all these procedures, while the drain is connected with the intake system, it is advisable to keep it clamped to prevent accidental introduction of external air through it.

25.1.4.2 PE Drainage

As mentioned above, because the liquid tends to collect downwards, the PE drain tube should be positioned from the posterior direction or possibly with the tip pointed towards the diaphragm. The rest of the maneuver is almost identical to that of placement of the drain for PNX drainage, possibly choosing the intercostal space to be underneath the one that would be used in PNX cases. It is also useful to execute the maneuver under ultrasound guidance.

With pleural empyema the simple chest tube is not decisive. If an empyema is established, the thoracic effusion is "organized" with the formation of fibrin agglomerates closely adherent to the parietal pleura. Very often the positioning of the drainage tube does not lead to leakage. If this occurs, the only possibility is video thoracoscopy. Video thoracoscopy is a minimally invasive surgical technique that allows for the removal of pleuroparietal adhesions. To flush the pleural cavity abundantly with the best possible bath for the pleural space, one (preferably two) chest tubes (apical and basal) under direct vision should be positioned [1, 2].

Closed suction system: Once it has been inserted, the chest tube must be connected to a collection system for draining the air or fluid from the pleural space. The basic requirement is that it must be unidirectional to prevent air or fluid going up into the pleural cavity accidentally (i.e., it is a closed circuit).

The concept of the closed suction system was established in 1872 when Playfair used a water valve to prevent air from going up into the chest through the drainage tube. However, the "father" of the modern chest drain is Gothard Bulau. The system of several bottles which he designed in 1891 still bears his name. He was the first to include the operation of negative pressure within the pleural cavity and to understand the importance of not avoiding contact between this and atmospheric pressure, thereby describing pleural empyema drainage by siphoning. It was during the Second World War that chest drainage and thoracentesis replaced thoracotomy which, until then, was largely routine for chest injuries.

Three elements have a fundamental role in the various types of closed drainage systems: gravity, positive pressure and suction.

- gravitational force causes the passage of air and liquid from a higher pressure level to a lower one. Hence, drainage should be in a lower position than the patient's chest to prevent the return of the drained material and the consequent risk of infection;
- drainage combines a higher pressure area

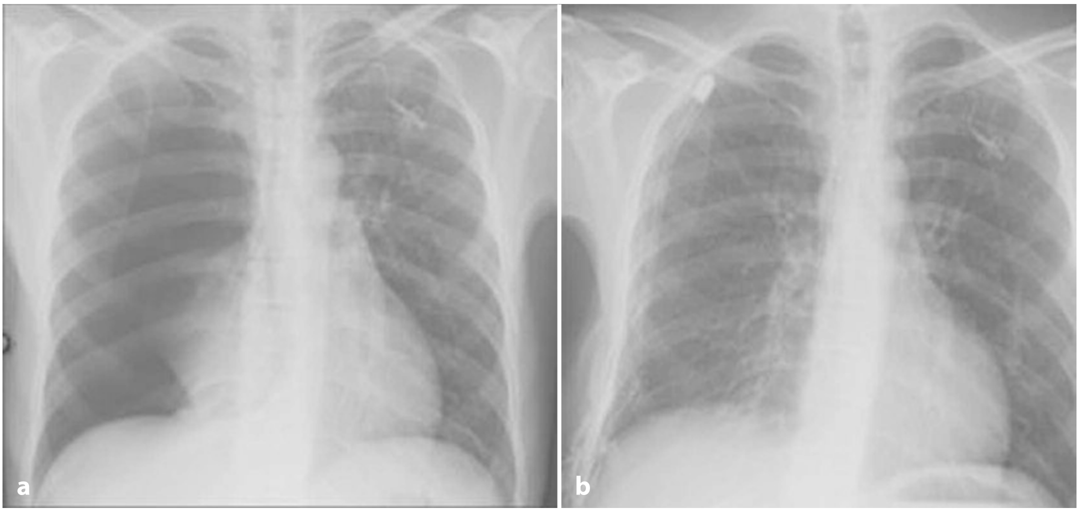

Fig. 25.5 a Right PNX; **b** quite complete resolution of the radiographic picture after the insertion of the drainage. From [13]

created in the pleural cavity due to the pathological presence of air or fluids (>762 mmHg) with a lower pressure (761 mmHg) so the material to be drained passes from the positive pressure area to that of lower pressure;

- addition of a suction system ensures a faster and more effective evacuation of gas and fluid.

The categories of collection systems which we referred to previously invented by Bulau are classified as the one-, two- or three-bottle methods. Glass bottles are used very rarely. Instead, there is another compact system, Pleur-Evac, named after the first manufacturer that made this system available on the market. However, the operating principle is the same as for the Bulau bottles.

In the one-bottle method (also called the "drop method"), the chest tube is connected to a drop tube that ends in a jar containing sterile distilled water. The cap that seals the jar is fitted with two stiff tubes. The first is a long tube, connected to the tube that goes to the patient, whose distal end is immersed in ≈2 cm of the distilled water at the bottom of the jar (which prevents further entry of air into the chest). The second is a shorter tube connected to the external environment, which allows air to escape from the evacuated pleural space and to be collected in the same bottle (Fig. 25.6).

The draft creates an evacuative one-way mechanism called a "water valve", which is essential for the removal of air and fluid in all the chest drainage systems used. This system serves three purposes, it: (i) ensures a unidirectional path for gas and fluid flowing from the thoracic cavity to the outside and not *vice versa*; (ii) ensures the display of air leaks; (iii) re-establishes a pressure difference between the chest cavity and the external environment.

During exhalation, when the pleural pressure becomes positive, the pressure in the immersed tube also becomes positive; if the pressure inside the tube is greater than the height of the immersed tube, the air or liquid penetrates the jar. During inspiration, when the pleural pressure is negative, a small quantity of liquid goes up into the immersed tube, without air return. The importance of this rise indicates endothoracic inspiratory depression, especially if the tube is equipped with a graduated scale (calibrated in centimeters), it becomes like a "pressure gauge" capable of measuring intrapleural pressure. These changes in pressure during respiration are responsible for fluctuations of 5–10 cm in the water valve column,

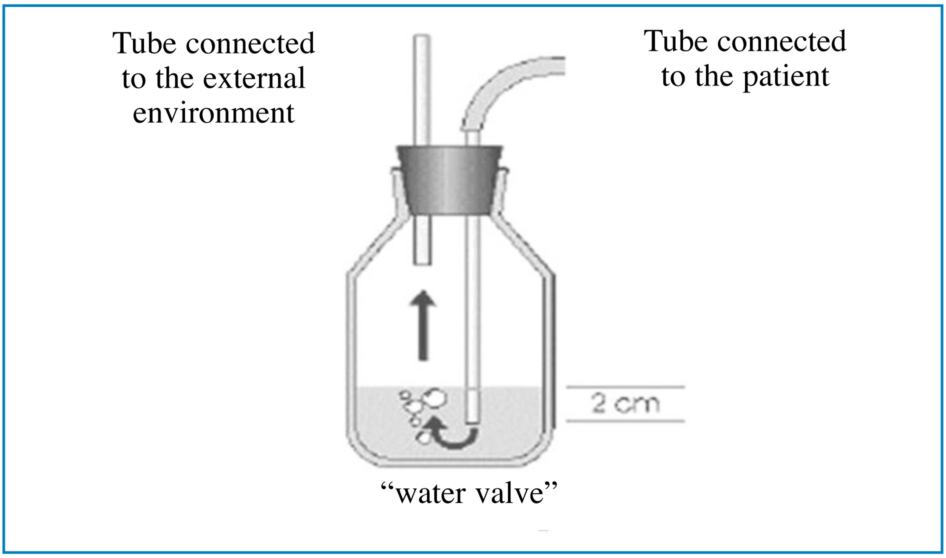

Fig. 25.6 The Bulau “one-bottle method”. The distal end of the chest tube is immersed in 2 cm of distilled water, a second tube is connected to the external environment. Modified from [13]

and show correct functioning of drainage and the patency of the tube.

It is necessary to keep the immersion of the water valve connection at a level of 2–3 cm. If it is barely immersed (for instance, if the bottle is tilted while moving it) there is the risk of rising air. If it is over-immersed, a hydrostatic counter-pressure will occur, which will hinder the drainage of the pleural cavity (a phenomenon that also occurs with large amounts of drained material). The bottle should always be placed on the floor ≥40 cm below chest level because the gravitational force largely contributes to adequate drainage of the pleural space.

The two-bottle method always features a water valve chamber, complemented by a jar for liquid collection. The operation is similar to that for the one-bottle method, but in this case the valve system is not affected by the drained liquid (Fig. 25.7). Its use is advisable, especially for the drainage of substantial effusions. Its major drawbacks are the result of it being cumbersome (problematic for deambulation of the patient), and the large dead space.

The three-bottle method is similar to that of the two-bottle method. The addition of a third bottle allows control of the amount of aspiration. It is used if it becomes necessary to apply suction to drain significant air leakage (e.g., in the event of pulmonary resection or traumatic lung lesions).

The drained fluid from the pleural cavity flows directly into the collection chamber. The air then passes into the second bottle with the water valve, where bubbles are formed. Thanks to the connection in series between the second and third jar, the drained fluid reaches the third bottle, where it is evacuated through the suction system (Fig. 25.8).

The third bottle added to the drainage system limits the negative pressure transmitted to the patient's chest. It consists of: (i) a control tube, graduated, open to the external environment, passing through the cap of the bottle and immersed in sterile water to a depth of ≈20 cm; (ii) a shorter tube connected to the water valve bottle; and (iii) a tube that connects the third bottle to the suction source. Accurate adjustment of the aspiration level is required because if it is too high it may cause hematoma formation at the point of catheter insertion or invagination of tissue in the fenestrations of the drain tube.

In the three-bottle method, the maximum level of suction applied to the chest corre-

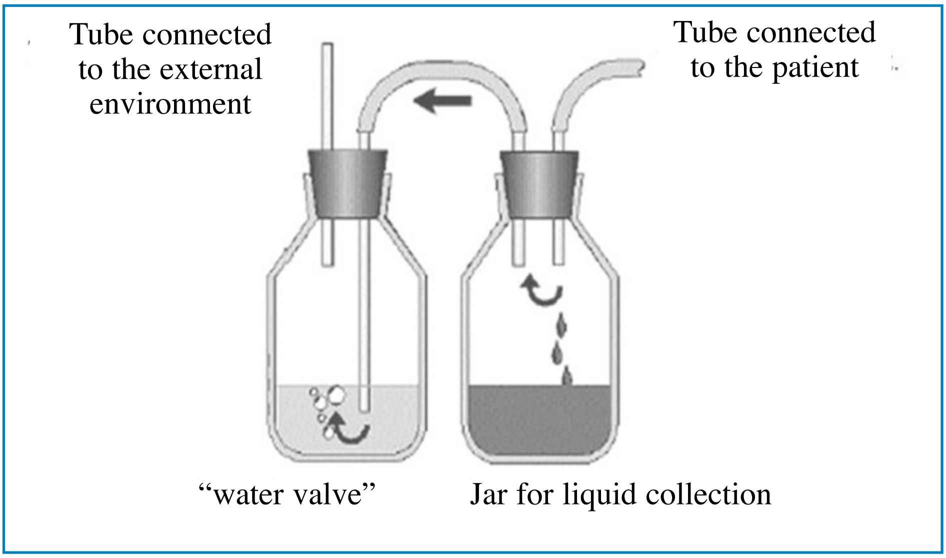

Fig. 25.7 The Bulau "two-bottle method". The concept is similar to that of the one-bottle method, but the valve system is not affected by the drained liquid. Modified from [13]

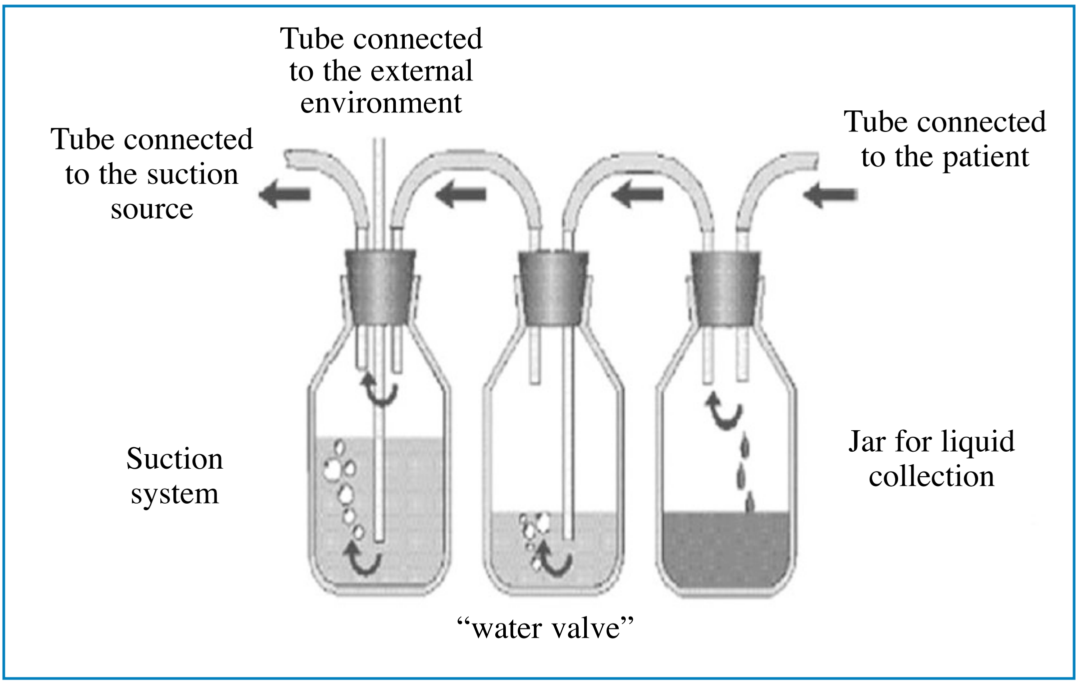

Fig. 25.8 The "three-bottle method". The addition of the third bottle control the amount of aspiration. Modified from [13]

sponds to the tube immersion depth: if the latter is immersed by 20 cm, the aspiration level will correspond to 20 cm of water. The central tube immersed in water therefore enables adjustment of the suction source applied to the pleural cavity. If the applied pressure is greater than the tube immersion depth, external air will enter the third bottle, forming bubbles in the liquid and balancing the pressure inside the jar.

The three-bottle method has been replaced by the sterile disposable device Pleur-Evac. It has the advantages of being less bulky, single-use (no need to empty the collection), unbreakable, compact, lightweight, as well as easy to move and operate [4]. It can be positioned on the floor or suspended next to the patient's bed, allowing accurate measurement of collected volumes without requiring maintenance during drainage. It also has dual protection against high positive or negative pressures.

The chambers of this device are equivalent to the traditional Bulau three-bottle method. They include a graduated collection chamber that measures the drained volume more accurately, a second chamber with a water or mechanical valve, and a suction chamber controlled by a water or mechanical control device (Fig. 25.9).

The collection chamber allows for the easy and accurate reading of the drained fluid. The nurse can record variations on a daily basis with a line inserted into a chart that indicates the time of the reading. Hence, any operator can assess (in real-time) the evacuated fluid from the chest during the postoperative hospital stay.

Fig. 25.9 The compact sterile disposable device Pleur-Evac has replaced the Bulau system. The chambers of this device are equivalent to the traditional three-bottle method (courtesy of Teleflex)

The water valve chamber is connected to the water collection chamber and ensures the unidirectional nature of the system. Pleur-Evac is also a diagnostic tool: the narrow tube is calibrated as a water manometer to measure variations in endopleural pressure. The drainage units are equipped with a protection device against high and negative pressures. They are equipped with an "anti-siphon valve". This is a floater at the top of the second chamber that protects the water chamber in the event of the tubes being squeezed or milked, thereby avoiding reflux in the collection chamber. Along with this valve there is an additional security system: a manual valve for high negative pressure. This valve enables evacuation of negative pressure through a temporary opening to the external atmosphere.

The suction control chamber is equivalent to the third bottle in the Bulau system. In the water-control system, the pressure suction is created by the height of the water column, usually regulated (as indicated above) at ≈20 cmH_2O. The third chamber, just like the second, has a "U"-shaped tube in which the shorter arm is connected to the external environment whereas the larger arm contains the water column. The total negative pressure transmitted to the patient is determined by the height of the water column in this chamber and not by the wall suction level.

The Thopaz drainage system (Medela AG, Baar, Switzerland) is a new compact digital reusable device that is not connected to the vacuum aspiration of the room's wall, and this feature gives the patients an unrestricted mobility. It makes the bed restriction unnecessary, permitting the early patient mobilization. Based on the patient's air leak, regulated negative pressure is applied close to the chest. A digital display shows actual and long-term data in real time as well as a 24-hour graph or the

Fig. 25.10 The Thopaz digital drainage system (courtesy of Medela AG). It permits the early patient mobilization. A digital display shows data and allow decisions in chest tube management by healthcare

air leak for easy tracking of therapy progress and timely and objective decisions in chest tube management (Fig. 25.10). In case of apical bullae, a segmental resection of the lobe can be done. The operation can be performed using a thoracoscopic approach using a stapler to resect the segment of the lobe (Fig. 25.11).

25.2 PM

PM, also known as mediastinal emphysema, is characterized by extraluminal air in the mediastinum [5.6]. PM, albeit very rarely, can be caused by various medical conditions and can often be accompanied by PNX, PC, pneumoperi-

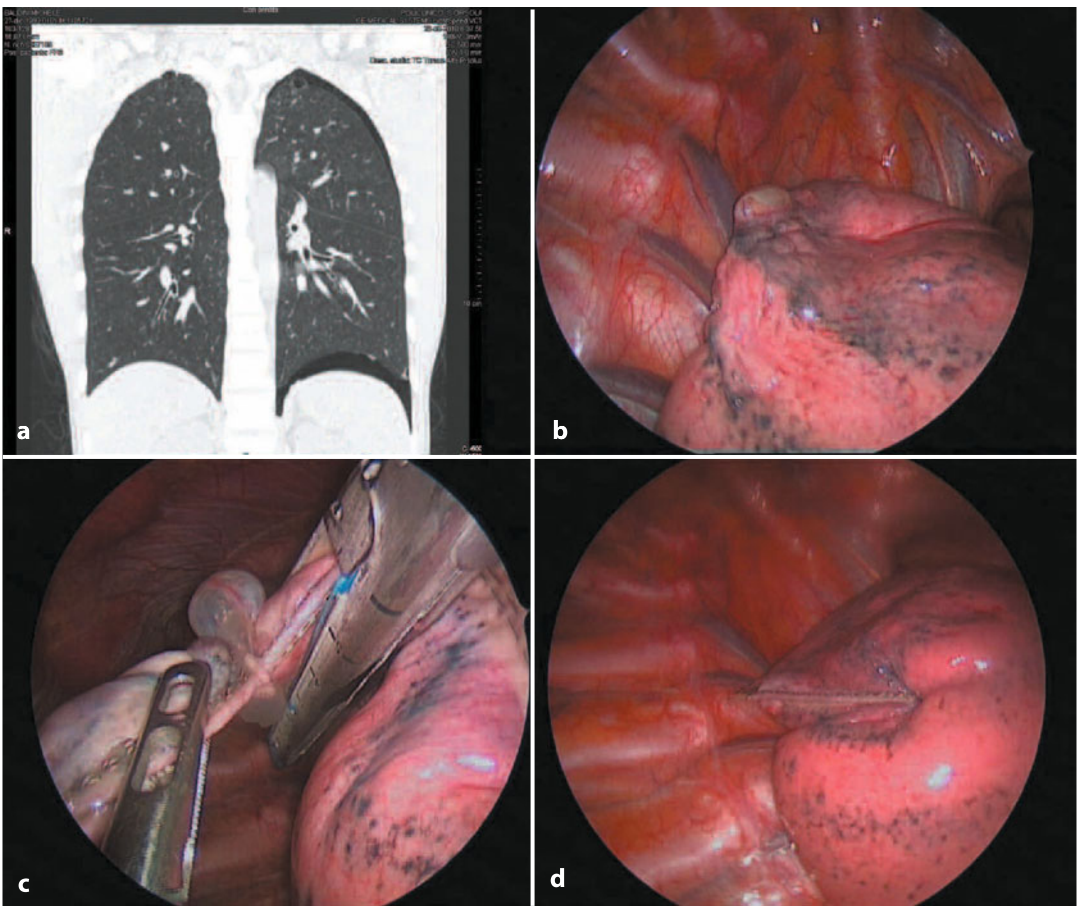

Fig. 25.11 a CT of subpleural apical bubbles complicated by pneumothorax; **b-d**, thoracic apical pulmonary resection

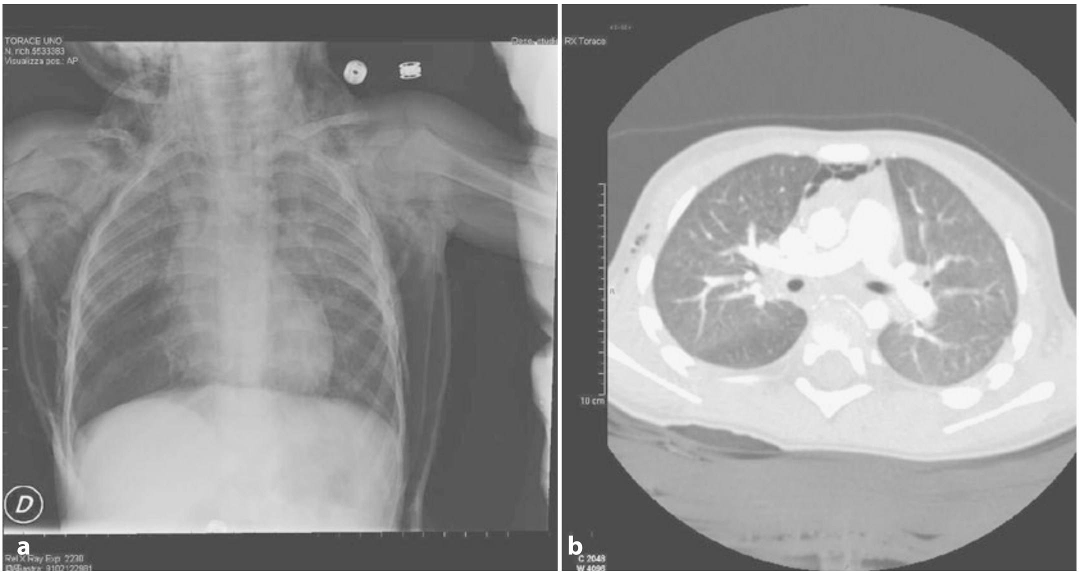

Fig. 25.12 a X-ray of left pneumothorax with pneumomediastinum; **b** CT of the pneumomediastinum

toneum or retropneumoperitoneum.

The air may collect in the mediastinum due to alveolar rupture, lacerations of the tracheobronchial tree, gastrointestinal (especially esophageal) ruptures, or direct passage through the cervical region, the retroperitoneum or the chest wall [7, 8].

25.2.1 Etiology and Pathogenesis

The most common cause is the rupture of alveoli, which occurs if there is high intra-alveolar pressure (obstruction of the airways, mechanical ventilation), or it may be due to lesions in the alveoli wall (pneumonia, emphysema, respiratory distress). Tracheobronchial lesions or perforation of the esophagus wall (spontaneous or iatrogenic) are less common causes of PM. Air can enter the mediastinum also from the head and neck (facial fractures, laryngeal injury, tracheostomy) [5].

PC is usually a result of penetrating trauma or cardiac surgery. It can rarely be caused by the same mechanisms that cause PM but in this case much higher pressures are required. However, it arises with PM [7].

25.2.2 Clinical Features

PM is usually asymptomatic. It can rarely cause chest pain or dyspnea. Stretching of the mediastinal pleura due to PM can lead to PNX. In exceptional cases, mediastinal pressure may be such as to lead to unconsciousness or hypotension due to decreased cardiac venous return [9].

At times, PM is the first clinical manifestation of a pathological disorder arising in the mediastinum. In this case surgical exploration of the abdomen is not advisable unless it becomes necessary in cases of doubt [10].

25.2.3 Diagnosis

PM is diagnosed directly by an experienced radiologist using chest radiography [7, 11]. It shows characteristic signs caused by the abnormal distribution of the gas formed around the organs in the mediastinum (Fig. 25.12). Free extrapleural air at the lung apex can easily be confused with PNX, as can back sternal PM extension. It is always useful to carry out chest radiography in two projections. Pneumomediastinal air collections tend to elevate and outline the thymus gland, whereas with PC air usually surrounds the heart (including the inferior aspect) and the pericardial sac is visible as a white line. These differentiating points are very useful if bilateral medial PNX occur.

Thus, we can identify a continuous diaphragm sign (air between the diaphragm and heart), Naclerio's V sign (the air draws the lateral margin of the descending aorta, predominantly but not specifically, in the case of esophageal rupture), the ring sign around the artery (air that surrounds the extracardiac mediastinal portion of the pulmonary artery), the extrapleural air sign (rounded air bubbles between the parietal pleura and diaphragm) and the spinnaker sign [7, 12]. A chest CT may be required to resolve diagnostic uncertainty [7].

Note The contents of this chapter are partially based on *Drenaggio pleurico e mediastinico nei versamenti pleurici e nello pneumotorace* (Lima M, Dòmini M, Gregori G, Randi B) in: Mirabile L, Baroncini S (2012) Rianimazione in età pediatrica, Springer, Milan, pp 599-611.

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