Airway Stenting in Interventional Radiology

Xinwei Han
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Springer

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ISBN 978-981-13-1618-0 ISBN 978-981-13-1619-7 (eBook)
https://doi.org/10.1007/978-981-13-1619-7

Library of Congress Control Number: 2018951072

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The first edition of Dr. Han and Dr. Wang book is interesting and well written, providing a comprehensive and updated volume and addressing the goal expressed in the title *Airway Stenting in Interventional Radiology*. Airway disease has been described in a clear and meticulous way, starting from histology, passing to anatomy, and ending up with the procedure. In a discipline such as interventional oncology, which has changed considerably in the last 15 years, this book is innovative because it includes not only a precise description of the procedure but also possible complications related to the procedure and their management, making the book technical as well as clinical at the same time.

The editors and their contributors have done an outstanding job in presenting a challenging topic in an easy way, accessible to the reader.

This book does provide systematic instruction in the techniques of airway stenting at either a basic or advanced level. I'm sure that it will become an important reference for all interventional radiologists; in fact, it will be essential for resident at the beginning of their training, but also useful for more experienced fellows and consultants who will find crucial information and important tips. Moreover, anatomy description and radiological measurement are detailed, even for nonradiologists.

Dr. Han and Dr. Wang and their colleagues have done a meticulous job in illustrating and cross-referencing the book. Moreover, the use of tables and boxes that summarize key points in the text are a really useful tool for the readers.

I strongly recommend this book for beginners and more advanced practitioners and congratulate Dr. Han and Dr. Wang for producing a high-quality text. I am sure that *Airway Stenting in Interventional Radiology* will become a useful tool for interventional radiologist as well as for other physicians performing these kinds of procedures.

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Acknowledgements

The authors thank Huabiao Zhang for comments and suggestions; they also thank Rui Zhang, Mingyue Wang, Yaru Chai, Jingjing Xing, and Dexuan Meng for their collection of Fingures in Chapter 2.

Contents

1 Tracheobronchial Histology, Anatomy, and Physiology

Hongqi Zhang, Xinwei Han, and Lihong Zhang

The respiratory tract, an important part of the respiratory system, is also called an airway because it is the passage that air travels in through the lungs. It is composed of the nose, pharynx, larynx, infraglottic cavity, trachea, and bronchi. Separated from cricoid cartilage, the upper part of the respiratory tract consisting of the nose, pharynx, larynx, and infraglottic cavity, it is called the upper respiratory tract, while the lower part of the respiratory tract includes trachea and all levels of bronchi below cricoid cartilage.

1.1 Tracheobronchial Anatomy

The lower respiratory tract, including trachea and all levels of bronchi, functions not only as the passage for oxygen intake and carbon dioxide emission but also as the organ used to remove foreign bodies inside the trachea and bronchi and adjust the humidity and temperature of entering air.

Lobar bronchi and other branches, such as the main bronchi, branch repeatedly in the lungs, which causes a dendritic shape to form. Because of its inverted tree shape, it is called the bronchial tree, and its branches have around 24 different levels (Fig. 1.1). The trachea (the trunk) is considered to be the zero level, and the left and right main bronchi the first level. The main bronchi stretch to the lung and branch out into the lobar bronchi, which are the second level of the bronchial tree. The right main bronchus branches out into three lobar bronchi, while the left main bronchus branches out into two lobar bronchi.

In the lung lobes, each lobar bronchus branches out into two to five pulmonary segmental bronchi, which are the third level of the bronchial tree. All segmental bronchi stretch out of the lobar bronchi at some angle.

The segmental bronchi bifurcate in the pulmonary segment repeatedly, their diameter continues to branch from 5–6 mm, and when the diameter of branches is less than 1 mm, bronchioles develop. In each pulmonary lobule, only one bronchiole exists and branches out into terminal bronchioles, which then branch out into respiratory bronchioles. Each respiratory bronchiole branches out into 2–11 alveolar ducts, which link alveolar sacks and alveoli [1, 2] (Table 1.1).

Technological improvement has make it possible and practicable to place inner stent in lobar bronchi and in the distal end of segmental bronchi, rather than only trachea, main bronchi, and intermediate bronchi.

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X. Han, C. Wang (eds.), *Airway Stenting in Interventional Radiology*,
https://doi.org/10.1007/978-981-13-1619-7_1

1.1.1 Trachea

The trachea, from the first cricoid cartilage (the six cervical vertebral level) to the lower edge of the last C-shaped cartilaginous ring (sternal angle plane, located at the junction of the fourth and fifth thoracic vertebral bodies), connects infraglottic cavity and carina. In the lower cervical area and upper chest, the trachea is called the cervical trachea and thoracic trachea, respectively.

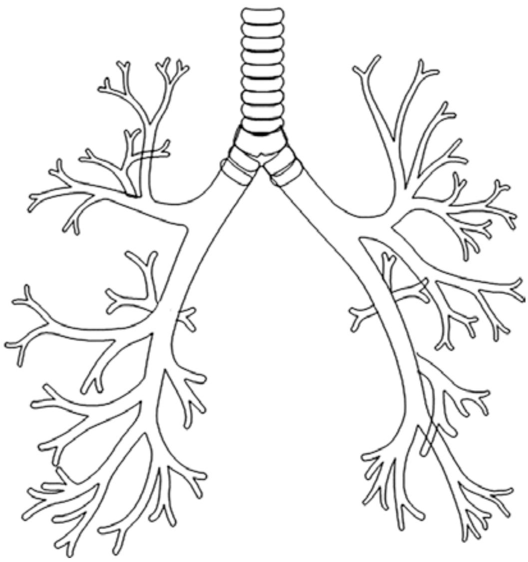

Fig. 1.1 Diagram of bronchial tree

With deep inhalation, the carina region will descend about 20 mm, while at the same time the trachea will extend about 20 mm. The larynx and infraglottic cavity will rise 15–20 mm, and the trachea will extend about 20 mm accordingly when head hypsokinesis. The cervical trachea is one-third and thoracic trachea two-thirds the total length of the trachea in adults.

1.1.1.1 Shape of Trachea

The shape of the trachea varies according to breathing patterns, age, and other factors. The shape of a cross section of the trachea is almost round in young adults. The diameter of the anteroposterior cross section of the trachea is nearly the same as that of the left-right cross section under calm breathing. In exhalations, the anteroposterior diameter contracts into the shape of a kidney, or a “C” or “U” shape (Fig. 1.2. Informed consent was obtained from all participating subjects, and the ethics committee of the first affiliated hospital of Zhengzhou University approved our study.). Many significant changes in shape happen with deep inhalations, coughing, and sneezing. For the elderly or pulmonary emphysema sufferers, the anteroposterior diameter lengthens, the left-right diameter decreases, and the cross section looks like the scabbard of a sword (Fig. 1.3).

Table 1.1 Branches of tracheobronchial tree in the human body

Branch level	Name	Lumen diameter (mm)	Lumen length (mm)	Comments
0	Trachea	18	120	
1	Main bronchus	12	48	
2	Lobar bronchus	8	19	
3	Segmental bronchus	6	18	
4	Subsegmental bronchus	5	13	
5–10	Small bronchus	4	5–11	
11–13	Bronchiole	1	3–4	Disappearance of glands and cartilage
14–16	Terminal bronchiole	1–0.5	2	Integrity of annular smooth muscles
17–19	Respiratory bronchiole	0.5	1–2	
20–22	Alveolar duct	0.4–0.5	0.5–1	
23	Alveolar sac			
24	Alveolus	244 μm	238 μm	

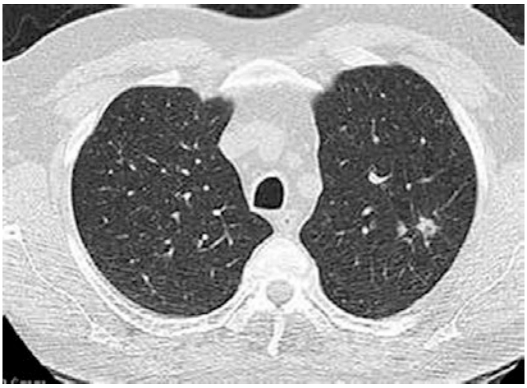

Fig. 1.2 Trachea in "C" or "U" shape

Fig. 1.3 Scabbard-shaped trachea

The inner diameter of the trachea may be the most variable line in human organs. The individual difference varies considerably (according to anatomical literature, for adult men and women, the variation range of the transverse diameter is 9.5–22.0 mm, and that of the sagittal diameter is 8.0–22.5 mm). If a stent is placed in the inner trachea, a multislice spiral computed tomography (MSCT) scan is performed using a special mediastinal window 400–500 HU wide with a level of −50 to −100 HU to measure the inner diameter of the sufferers' trachea [3]. The diameter and specification of the tracheal inner stent should be measured individually. The back wall of the commonly seen C-shaped or U-shaped trachea is tabular. The average inner transverse diameter is approximately 16.5 mm, while the sagittal one is about 15.0 mm.

The length of the trachea shows notable variation between a living body and a corpse. The measurement results from living adults are different to that of corpse. Because the action of respiration affacts the length of trachea. The length of the trachea also changes notably at different breathing amplitudes. It lengthens downward during deep inhalations and contracts upward during deep exhalations. When the head rises and falls backward, the trachea can extend approximately 15 mm upward.

1.1.1.2 Structure of Trachea

The wall of the trachea is composed of tracheal cartilages, smooth muscle fibers, and connective tissues.

1. *Tracheal cartilages*. Tracheal cartilages are hyaline cartilages of horizontal C or U shape with a half-ring structure containing backward openings. The perimeter of tracheal cartilages is about two-thirds that of the trachea. There are 14–17 C-shaped cartilaginous rings in the human body, and men on average have one more than women. The first C-shaped cartilaginous ring at the side of the head is high and wide, while others are similar in shape and size with a height of 4 mm and a wall thickness of 2.2–2.5 mm. C-shaped tracheal cartilages develop to the point of calcification at the ages of 40–50 years. Tracheal cricoid cartilages have a supporting function as stents, so they can keep the inner cavity of the trachea open forever to ensure the normal functioning of respiration ventilation function. C-shaped tracheal cartilages with gaps show significant variation in lumen diameter when external pressure or expansion is exerted, which should be given full consideration when tracheal inner stent placement is to be carried out.
2. *Membranous wall of trachea*. Membranous wall of the trachea refers to the elastic fibers and smooth muscles in the back wall of a closed trachea. The membranous wall possesses a certain amount of elasticity. The rear part of the membranous wall is closely connected to the esophagus. The elasticity of the membranous wall makes it possible for giant

food pellets to descend into the stomach smoothly. Giant food pellets, giant esophageal neoplasms, as well as inner stents with relatively large diameter in the esophagus can all push trachea posteriorly, leading to tracheal stenosis and dyspnea.

3. *Annular ligaments*. Annular ligaments are also called tracheal ligaments, whose adjacent cricoid cartilages are connected together by annular ligaments formed by elastic fibers. Annular ligaments possess elasticity and a certain flexibility. The change of length of the trachea in connection with breathing and raising of the head mainly depends on flexible changes in the annular ligaments.

1.1.1.3 Adjacency of Trachea

The cervical trachea is located at the anterior middle of the neck and adjacent to the thyroid and carotid sheath on the side. The isthmus of the thyroid covers the front part of the first, second, and third tracheal C-shaped cartilaginous rings (occupied 58.7% of total number). For people who are old or who have short necks, the isthmus is relatively low with enormous width variation ranging from covering one C-shaped tracheal cartilaginous ring to seven. While the beginning part of the trachea is shallow and almost close to the skin at a depth of 5–20 mm, it gradually gets deeper in the lower part of the neck and can attain a depth of 40 mm below the skin at the suprasternal fossa. Its anatomical features should be given due attention when performing a tracheotomy.

The thoracic trachea, among left and right pleural sacs and lungs in the superior mediastinum, connects to the manubrium sterni, thymus or thymus remnants, and great vessels (ascending aorta, aortic arch and superior cena cava) in the front, and is connected to the esophagus and parallel to it vertically in the back. There are repeating laryngeal nerves in grooves between the trachea and the esophagus. The trachea is surrounded by areolar tissues, which contain lymph nodes (there are abundant lymph nodes around the lower part of the trachea). Enlargement of the lymph nodes can exert pressure on the trachea and lead to an irritating cough when mild and result in fatal tracheal stenosis when severe. When a thymic tumor or ascending aortic aneurysm exerts pressure on the trachea from front to back, or when an esophageal lesion or descending aortic aneurysm exerts pressure on the trachea from back to front, this leads to tracheal stenosis.

The trachea is surrounded by loose connective tissues, which gives the trachea a significant range of motion so that it is able to move toward the same side as the head does. Because the trachea and surrounding structures are loosely fixed, lesions in the lung, pleura, and other adjacent areas can pull or thrust the trachea, causing displacement. On the one hand, the loosely fixed displaceability is regarded as a self-protection mechanism that keeps the inner cavity of the trachea open. On the other hand, it also protects the trachea from external compression and compression-induced tracheal stenosis that are the results of pulmonary and pleural space-occupying lesions.

Surgical treatment of esophageal cancer has been advocated recently. It features extensive and radical resection of the esophagus, as well as esophagus-stomach anastomosis in the neck. The stomach is lifted to pleural cavity and post mediastinum where the esophagus primarily existed. With operation wounds, bleeding, and exudation, the subsequent organization and fibrosis cause the intrathoracic stomach to become closely linked to the back wall of the trachea and integrated with the trachea, forming a new tracheal–intrathoracic stomach with an anatomically adjoining relationship. If a relapse of esophageal cancer, gastric wall ulcer, gastric wall ischemia, necrosis, or perforation occurs, the intrathoracic stomach—airway fistula can be developed; or if tumor is not resected completely, stereotactic radiotherapy (such as X-knife radiosurgery, γ-knife radiosurgery, or intensity-modulated radiation therapy) should be performed for residual tumor after the operation. The total doses of radiotherapy are calculated on the basis of the radiation tolerance doses of the trachea (6000~8000 cGy). For stomachs with low radiation tolerance doses (only 4000 cGy), overdoses of radiation will bring injuries, ulcers and perforation. In this condition, gastric juice flow to trachea through intrathoracic stomach—airway fistula, causing a series of pathological changes of lung injuries and displaying a whole string of complicated clinical manifestations.

1.1.2 Carina

The carina is generally known as a special anatomical marker at the bottom of the trachea. It is described as “carina cristae,” which is treated as the intersection of the trachea and bilateral main bronchial branches. Morphologically, no complete, systematic, and detailed investigation has been carried out on the carina. A search of the domestic and foreign literature revealed that it remains an anatomical blind spot. The issue whether the carina is an anatomical marker or an anatomical region has been neglected, from the point of view of either human anatomy or clinical medicine and surgery. With the popularization of interventional radiology, especially the wide application of inner stents at the lower part of the trachea and inner stents at the opening of the left and right main bronchi at the junction of the trachea and main bronchi, researchers have started to focus on producing a detailed understanding of the anatomical structure of the carina.

1.1.2.1 Shape of Carina

In the traditional view of anatomy, the trachea bifurcates at the bottom, from which the left and right main bronchi branch. Here a special change can be observed in terms of the shape of the tracheal rings. The middle part of the bottom of cartilaginous rings shows a downward tendency to form a sharp protrusion. The crescent-shaped carina cristae is an upward facing bulge in the trachea that forms upon bifurcation of the trachea. The cricoid cartilage looks like an inverted saddle (Fig. 1.4).

Fig. 1.4 The saddle and the inverted saddle

The carina is formed at the intersection of the bottom of left and right main bronchi and is known as the carina of the trachea. Generally, the bottom of the bilateral main bronchi is smooth, while the angle of the carina is sharp. The intersection angle of bilateral bronchi equals the angle of bifurcation of the trachea, which, 60° to 85°, is the angle of the carina in clinics . The size of the angle is related to the shape of the thoracic cage. The wider and shorter the thoracic cage, the larger the angle, and vice versa.

Dr. Xinwei Han treats the carina as a special anatomical zone between the trachea and the bilateral main bronchi. When the upper bound is the bottom of a C-shaped cartilaginous ring at the lowest part of the trachea, the lower bound is the top of the first C-shaped cartilaginous ring at the bilateral main bronchi. The structure of the carina includes an annular ligament of the trachea, a cartilaginous ring in the shape of an inverted saddle, an annular ligament of the left main bronchus, an annular ligament of the right main bronchus, and a section of membranous wall in the rear of the annular ligament of the right main bronchus. An inverted triangular or trapezoidal section is arranged with the inverted saddle-shaped special cartilaginous ring at the center (Fig. 1.5). From the point of view of either anatomy or histology as well as function, this section is different from both the trachea and the main bronchi. The carina is regarded as a special anatomical zone, referred to as the carina region.

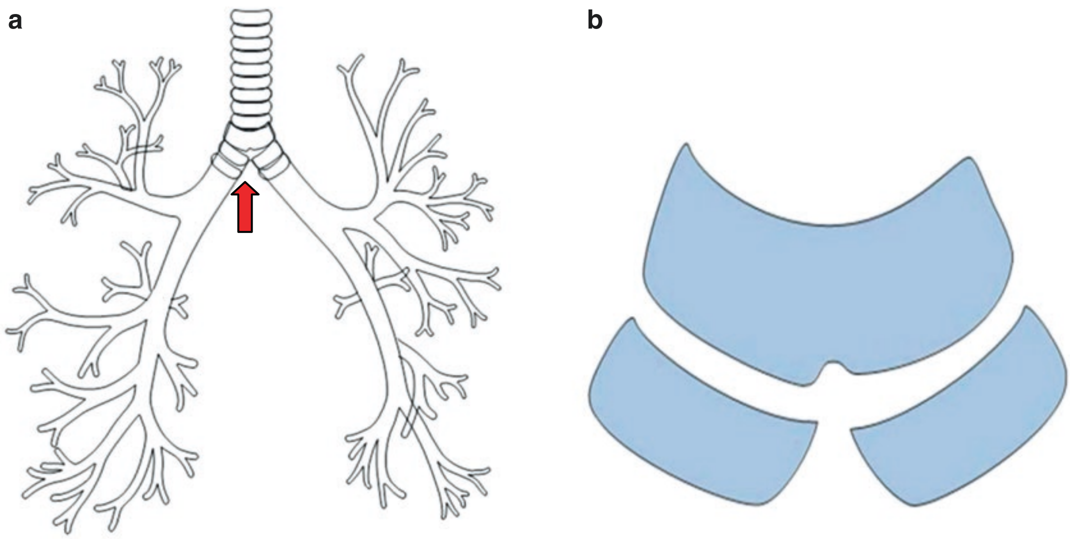

Fig. 1.5 Diagram of carina of trachea: (**a**) bilateral main bronchi in trachea-carina region; (**b**) local amplification of carina region

1.1.2.2 Adjacency of Carina

The left atrium is located at the anterior inferior part of the carina. Enlargement of the left atrium due to heart disease can push the bilateral main bronchi and carina to increase the angle of the carina.

The right front part of the carina is in the top of the vena cava. An enlarged transitive tumor of the lymph node often appears between the carina and superior vena cava. Enlarged lymph nodes are able to compress the right main bronchus and carina, leading to carina stenosis, and they can compress the superior vena cava, resulting in superior vena cava compression syndrome.

The area around the carina, especially the anterior and inferior part of carina, has the widest distribution of mediastinal lymph nodes. Various types of tumors, such as those of lung cancer, esophageal cancer, and stomach cancer, may lead to mediastinal lymph node metastasis concentrating around the area of the carina, which results in polystenosis in the central airway. Polystenosis in the central airway includes the lower part of the trachea, the carina region, and the left and right main bronchi; as a result, these polystenoses will lead to dyspnea and even asphyxia and death in patients when serious. A Y-shaped integrated self-expandable inner stent and delivery system for the airway created by Dr. Xinwei Han are irreplaceable therapy for this kind of compound main airway stenosis.

The rear of the carina is close to the esophagus. If an esophageal neoplasm grows forward, it directly pushes the carina and causes fatal stenosis in the carina region, which is a main airway with three divergences. Accordingly, if an esophageal tumor in the progressive stage grows outward, it can damage airway walls in the carina region directly, resulting in a connection between esophagus and the carina region, which is one of the three divergences. As a result, esophagus-carina fistula can form.

After surgical resection of esophageal cancer, the stomach develops into the pleural cavity and localizes around the esophageal bed, which originally occupies the posterior of the mediastinum and forms an intrathoracic stomach. The intrathoracic stomach closely connects to the back wall of the tracheal carina and is integrated with the carina. In the case of relapse of the tumor, gastric ulcer, gastric ischemia, necrosis, and perforation may occur, resulting in intrathoracic stomach–airway fistula; or if the tumor is not resected completely, stereotactic radiotherapy should be performed for residual tumor after the operation. Overradiation will lead to damage to the gastral cavity in the area originally occupied by the esophageal bed. The intrathoracic stomach–

airway fistula occurs because of ulcer and perforation of the gastric wall, and etch of the wall of digestive tract by gastric juice.

1.1.3 Main Bronchi

There are two main bronchi, the left and right main bronchi, composing the first level of the bronchial tree. The main bronchi are able to move downward and outward in a diagonal direction. So far, the best technique to measure the inner diameter and length of the airway is a special mediastinal window (fat window) using MSCT transverse scan imaging. Certain image reformation and data reconciliation are carried out together with a CT image measurement of the cross section or diameter of the main bronchi that move in a diagonal direction.

1.1.3.1 Structure of Main Bronchi

The structure of the main bronchi wall, similar to that of the trachea, is also composed of main bronchial C-shaped cartilaginous rings, annular ligaments, and membranous wall. The difference between both of them is that the C-shaped cartilaginous rings are relatively small, while the membranous wall of smooth muscles and fibrillar connective tissues is relatively wide. At this point, the contractility of main bronchi becomes stronger, the lumen becomes thinner, and the air turbulence becomes more intense with coughing, expectoration, and sneezing, which makes it easier for sputum and foreign bodies to be eliminated. While the left main bronchus is longer with seven to eight cartilaginous rings, the right main bronchus is shorter with only three to four cartilaginous rings.

1. *Left main bronchus*. The left main bronchus, usually 40 mm long with an average of 48 mm for men and 45 mm for women and 10 mm inner diameter. The average transverse diameter is 11.2 mm for men and 9.3 mm for women; furthermore, the average sagittal diameter is 9.3 mm for men and 7.5 mm for women.
2. *Right main bronchus*. Compared to the left main bronchus, the right main bronchus is both short and thick. Usually the length is 15–20 mm with an average of 21 mm for men and 19 mm for women. Its inner diameter is above 10 mm, and the average transverse diameter for men is 15.1 mm and that for women is 13.1 mm. The average sagittal diameter for men is 14.1 mm and 9.3 mm for women.

1.1.3.2 Adjacency of Main Bronchi

There are abundant lymph node groups around the main bronchi. Mediastinal lymph node metastasis in thoracic malignant tumor may emerge mainly in the area around the main bronchi and compresses main bronchi to stenosis.

1. *Adjacency of left main bronchus*. The rear of the left main bronchus is near the esophagus, thoracic duct, and descending aorta. Esophageal cancer or descending aortic aneurysm pushes on the left main bronchus. The middle part of the left main bronchus is bypassed by the aortic arch from above and the left pulmonary artery, which is in front of the aortic arch. It is difficult to expose the left bronchus in an operation because of the occlusion of the pulmonary artery and descending aortic aneurysm, which causes a relatively long segment bronchus stump in left lung resections. If a left main bronchopleural fistula occurs, and bullet covered inner stent closure treatment needs to be carried out; this kind of relatively long stump is good for the placement of an inner stent.

   With the surgical resection of esophageal cancer, the stomach is lifted to the pleural cavity. The intrathoracic stomach is around the area where the esophageal bed is originally located in the posterior mediastinum, so that it closely connects to the back wall of the left main bronchus. If a tumor relapse, gastric wall ulcer, and additional stereotactic radiotherapy on the residual tumor after surgery occur, overradiation will lead to injuries to the gastral cavity originally occupied by the esophageal bed. Ulcer and perforation of the gastric wall and etch of the wall of the digestive tract by gastric juice will result in intrathoracic stomach–left main bronchus fistula.

2. *Adjacency of right main bronchus*. The superior vena cava is located in the front of the right main bronchus. From backward to forward, the azygos vein bypasses the right main bronchus from above. The right pulmonary artery is at the bottom of the azygos vein. The right main bronchus is relatively short, which makes it easier to expose it during an operation. If a bullet-covered inner stent closure needs to be done to treat a right main bronchopleural fistula, attention should be paid to the fact that there is a very short or even no stump in order to choose the most suitable covered inner stent.

1.1.4 Intermediate Bronchus

The intermediate bronchus, a unique structure in the right part of the bronchial tree, extends from the right main bronchus. The section of the bronchus from the opening of the superior lobe to that of the middle lobe belongs to neither the superior lobe or the middle lobe without branches. Like the structure of the main bronchus, the wall of this section is also composed of relatively small C-shaped cartilaginous rings, relatively wide annular ligaments, and membranous wall. With the ability to contract, the intermediate bronchus becomes stronger, and its lumen becomes thinner; at the same time, the air turbulence becomes more intense, especially with coughing, expectoration, and sneezing, which are easier methods for the elimination of sputum and foreign bodies. The total length of the intermediate bronchus is 20–30 mm and its inner diameter is 10–11 mm. When inner stent interventional therapy is applied for intermediate or lower lobe bronchial lesions, it is an extremely useful structure to fix the inner stent.

There are abundant lymph nodes around intermediate bronchus. Metastatic lymph node enlargement can very easily compress intermediate bronchus, resulting in stenosis. If stereotactic radiotherapy is used for residual tumor after the surgery due to relapse or incomplete tumor resection, overradiation can lead to injuries to the gastral cavity where the esophageal bed is located. Ulcer and perforation of gastric wall, and etch of digestive intermediate bronchus wall by gastric juice will result in intrathoracic stomach–intermediate bronchus fistula.

1.1.5 Upper Lobe Bronchus

The lobe bronchus is the second level of the bronchial tree. Both lungs contain an upper lobe bronchus, but with different structures.

1.1.5.1 Upper Lobe Bronchus of Right Lung

The majority of upper lobe bronchi of the right lung are about 10–20 mm away from the carina. Almost at a right angle from the right edge of the right main bronchus after branching, the upper lobe bronchus of the right lung rises to the upper lobe of the right lung. Then it branches out into three segmental bronchi, anterior branch, apical branch, and posterior branch. The apical branch, ascending vertically, is treated as the direct extension of the upper lobe bronchus. When an inner stent is placed in the right upper lobe bronchus, a guide wire will enter the deep part of the upper lobe bronchus through the apical branch. It is beneficial to fix a guide wire in an inner stent. The length of the right upper bronchus is 10–20 mm and its width is 8–10 mm. While a few right upper lobe bronchi can branch directly from the lower part of the bronchus, the right main bronchus and intermediate bronchus will integrate together without any branches.

1.1.5.2 Upper Lobe Bronchus of Left Lung

The upper lobe bronchus of the left lung is 40–50 mm away from the carina. It branches almost in a horizontal baseline of the left edge of the left main bronchus. The left upper lobe bronchus is very short with 10–20 mm length and branches out into two branches, the top and the bottom branches. The top branch is equivalent to the right upper lobe bronchus, while that of the bottom, namely, the tongue, is equivalent to the right intermediate lobe bronchus.