Jose Pablo Díaz-Jimenez
Alicia N. Rodriguez
Editors

Interventions in Pulmonary Medicine

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ISBN 978-1-4614-6008-4 ISBN 978-1-4614-6009-1 (eBook)
DOI 10.1007/978-1-4614-6009-1
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2012951670

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To my wife Mercedes, to whom I owe so much, and who is by my side on the way of life.
To my father, my best friend.
To my grandchildren: Elia, Lluc, Quim, and Ferran from whom I am learning to live.
To Alicia Rodriguez, my dearest friend and superb pulmonologist, the true architect of this book.
To my mentors: Dr. J.F. Dumon from Marseille and Dr. D. Cortese from Mayo Clinic, who directed my first steps in Interventional Pulmonology.

Jose Pablo Díaz-Jimenez

To Manuel, Francisco, and Juan, who make my day everyday.
To Jose Pablo Díaz-Jimenez, always grateful to my great teacher and excellent friend.
To my mentors: Drs. M. Maxit, J.M. O'Donnell, J.F. Beamis, Jr., and A.W. Gray Jr., from whom I have learned that medical practice should be guided by kindness, knowledge, a strong work ethic, and a lot of common sense.

Alicia N. Rodriguez

Foreword

Interventional Pulmonology (IP) has been the most interesting and rewarding aspect of my medical career. In addition to benefiting patients, which is the main goal of Interventional Pulmonology, IP has brought me in contact with and allowed me to develop friendships with other IP physicians throughout the world. One such physician is Dr. Jose Pablo Díaz-Jimenez, one of the premier European interventional bronchoscopists. Dr. Díaz-Jimenez is widely respected internationally (recent past Chairman of the World Association for Bronchology and Interventional Pulmonology) and has greatly influenced the education of future IP physicians by his contributions to the medical literature and by organizing many educational courses and respiratory meetings in Barcelona and Sitges.

I have also been involved in the training of pulmonary fellows and I am very proud of Dr. Alicia Rodriguez who is a graduate of the Lahey Clinic Pulmonary Fellowship Program. Drs. Díaz-Jimenez and Rodriguez have collaborated in the past with the successful publication of their first IP book in Spanish in 2000.

This new collaboration between Drs. Díaz-Jimenez and Rodriguez brings together contributions by international IP experts to address current and future applications of IP. Sections on Basic Endoscopy cover anatomy, use of flexible and rigid bronchoscopy, and training. A section on Tracheobronchial Obstructions reviews the array of methods that are currently available to open obstructed airways. The section on Lung Cancer Diagnosis reviews important methods of detecting and diagnosing early, superficial airway tumors and diagnosing peripheral lung lesions. Lung Cancer staging with IP methods is becoming more and more commonplace, and this is addressed in the section on Lung Cancer Stratification. The last section on Interventional Pulmonology in Special Situations covers non-bronchoscopic IP procedures such as Percutaneous Tracheotomy and Medical Thoracoscopy and newer bronchoscopic therapies for emphysema and asthma.

The spirit of Interventional Pulmonology began with Dr. Jean François Dumon who perfected many interventional bronchoscopy techniques and shared his expertise with bronchcoscopists throughout the world through numerous publications, courses, and speaking engagements. Dr. Dumon has many disciples, including Dr. Diaz-Jimenez and myself and several authors in this book. This edition of *Interventional Pulmonology* by Díaz-Jimenez and

Rodriguez reflects the spirit of IP in that it offers a state-of-the art view of IP by bringing together international contributors who share their clinical IP expertise in procedures that if performed well can only benefit the care of patients.

Burlington, MA, USA John F. Beamis
Honolulu, HI, USA

Preface

Nothing beats the pleasure of seeing a finished work.

This book is a reflection of what we do everyday in the endoscopy room, and it would not have been possible without the collaboration of the colleagues who have participated, sharing their knowledge and expertise to clearly set out the fundamental concepts of this wonderful Interventional Pulmonology world.

I have been working in the interventional area for more than 30 years, and one of the main concepts that I have learned is that success in daily work is not on one individual, but it is only achievable when everybody works with the conviction of being part of a team.

It would not be possible to perform a complex treatment such as releasing the airway from an obstructive malignant tumor without each and every team member's participation, applying their knowledge and abilities in a coordinated and complementary fashion. As team members, we all share responsibilities. I believe one of the main ones is to make the whole team function based on these three mainstays: coordination, communication, and complement, since they are the keys of a successful work.

Since the advent of bronchoscopy in 1887, the field of bronchology and interventional pulmonology has demonstrated its clinical value with amazingly rapid developments. The last three decades have brought to us spectacular advances in technology and their clinical applications, which have led to lifesaving therapies. We can predict that we will see newer clinical applications and improvement in established techniques in the near future. These dynamic changes will bring together the scientists and clinicians interested in our specialty and further expand the field.

It is our duty to keep updating the state of the art and maintain a continuous progress. The scientific and clinical training of the respiratory endoscopist must rest on solid principles and remain in constant forward motion, and therefore, constant teaching and learning become our obligations.

During all these years we have received pulmonary fellows from all continents who have spent long periods of time with us or have attended our courses or conferences, teaching them interventions and also learning from them. We have also learned from very respected physicians of the Interventional Pulmonology field who have honored us with their presence, sharing their experiences and making this learning process extremely easy, as if we were in a family reunion listening and exchanging everyday experiences. At the end of the day, we were all enriched, and I believe all our patients benefited from our sessions and discussions.

Experience does not come only as a consequence of performing many procedures but also from having an open mind and listening to the advice and suggestions from other colleagues. The learning process takes a lifetime. At the beginning, we are all learners, and as time goes by, it becomes our turn to take the position of the teacher and to contribute to the growing number of fellows and residents interested in endoscopic procedures. What would have occurred if retired from daily practice Killian, Jackson, Andersen, Ikeda, Zavala, Hayata, Kato, Cortese, or Dumon had not transmitted their experiences to the rest of the scientific community? It would have been much more difficult for us to arrive to our present state of knowledge. However, the generosity of all of them made our way much easier.

Bertrand Russell said it is good from time to time to think on the present as if it were the past, and consider which of the elements of our time will enrich the permanent deposit of the universe and which ones will live and give life when our generation has disappeared. Having this contemplation, the human experience transforms and the personal experience vanishes.

With this in mind, I believe the teaching and learning process is crucial, and they both have to be taken with humility. To our teachers we always owe gratitude and respect, and when we become teachers, it is important to be generous, recognize limitations, and transmit what is worth, keeping always as a goal to benefit our patients in every possible way.

Following this line, Alicia and I would like to take this opportunity to thank the many teachers and colleagues around the world who helped us along the way, with their advice and continuous support:

– Dr. Udaya Prakash and Eric Edell form Mayo Clinic.
– The coworkers from the Bronchoscopy Department at Bellvitge University Hospital in Barcelona: A. Rosell, R. Lopez, and N. Cubero, and from the MD Anderson Cancer Center Team in Houston: R. Morice, G. Eapen, C. Jimenez., D. Ost, and BF. Dickey.
– The Pulmonary Department Team at Lahey Clinic in Massachusetts.
– The Pulmonary Department Team at Clinica Colon in Mar del Plata: L. Araya, N. Baillieau, R. Gonzalez Cuevas, S. Ruiz, C. Materazzi, and M. Rocha.

And finally, our especial thanks to all the colleagues who participated in this work, generously sharing their wisdom and making possible this small addition to the art of Respiratory Endoscopy. It is our hope that this book will contribute to improve our daily interventional pulmonology practice.

Barcelona, Spain Jose Pablo Díaz-Jimenez

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Part I

Basic Endoscopy

Tracheobronchial Anatomy

1

Juan Antonio Moya Amorós
and Anna Ureña Lluberas

Trachea

Introduction

The trachea or windpipe is a tube of approximately 12 cm length. In a lateral view, it assumes an oblique course, running from superoanterior to inferoposterior, from 23º to 34º related to the body's major axis. It ends up by dividing into two bronchial tubes at the level of the tracheobronchial bifurcation, which usually has an angle of 60º. Changes in the degree of angulation can orient to diagnose some conditions located distally to the bifurcation such as enlarged lymph nodes or left atrium dilatation in mitral stenosis. The tracheal tube extends from C6–C7 (limited by the cricoid cartilage superiorly) to D4–D5, approximately at 1 or 2 cm below a horizontal plane passing through the Louis sternal angle. Topographically its average length (12 cm as stated) is equally divided between the cervical and mediastinal region.

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External Morphology

The external tracheal layer configuration is characterized by the presence of roughness due to incomplete cartilage rings that are staggered and horizontally and segmentally distributed. Usually 20 rings are identified in the trachea.

In the cervical region, the tube has a flattened shape posteriorly, due to the absence of cartilage, so that the predominant diameter is the sagittal or anteroposterior (approximately 16 mm), but inside the chest, it predominates the transverse diameter (approximately 16 mm).

In the external tracheal wall, narrowing or depressions can be seen, produced by the imprint of organs in close proximity contacting to the tracheal wall. In the left side, two of them are visible: one due to the left thyroid gland lobe (neck) and the other one due to the aortic arch (mediastinum).

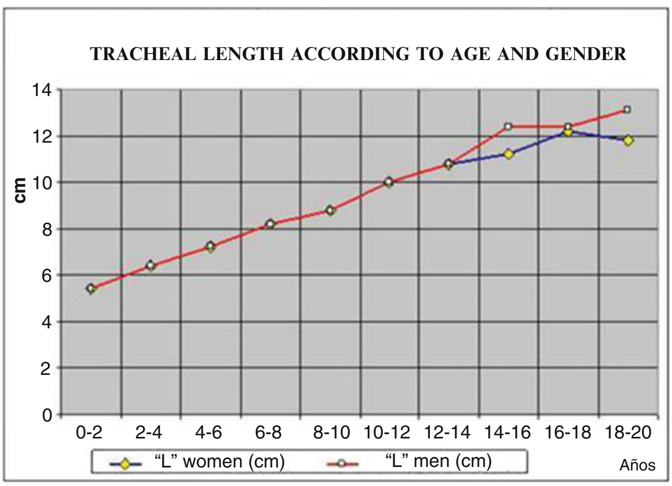
The posterior membrane closing the entire tracheal canal is flat, soft, and depressible; it is known as the *membranous pars* (Fig. 1.1).

The especial tracheal configuration and its elastic structure make it capable to elongate up to 1/3 of its length. This fact is of particular interest for tracheal reconstruction surgeries.

Dimensions of the trachea vary primarily according to age and less so with gender. Figures 1.2–1.5 present the normal size variations in all three axes, internal size, area, and volume.

J.P. Díaz-Jimenez and A.N. Rodriguez (eds.), *Interventions in Pulmonary Medicine*,
DOI 10.1007/978-1-4614-6009-1_1, © Springer Science+Business Media New York 2013

Fig. 1.1 Anterior view of the dissected trachea. Note the tracheal bifurcation angle of 60°: (*1*) anterior view—trachea and tracheal cartilage. (*2*) Tracheobronchial bifurcation. (*3*) Membranous pars or tracheal muscle. Unit of Human Anatomy and Embryology. Department of Pathology and Experimental Therapeutics. Universitat de Barcelona



	"L" women (cm)	"L" men (cm)
0-2	5.4	5.4
2-4	6.4	6.4
4-6	7.2	7.2
6-8	8.2	8.2
8-10	8.8	8.8
10-12	10	10
12-14	10.8	10.8
14-16	11,2	12,4
16-18	12,2	12,4
18-20	11,8	13,1

Medium length of the trachea increases similarly in both genders until the age of 14. After that it only increases in men.

Fig. 1.2 Medium length of the trachea increases similarly in both genders until the age of 14. After that it only increases in men

Among both genders, there are also differences in tracheal size especially in the sagittal and transverse axes, which are evident in tomographies and 3D reconstructions (Figs. 1.6 and 1.7).

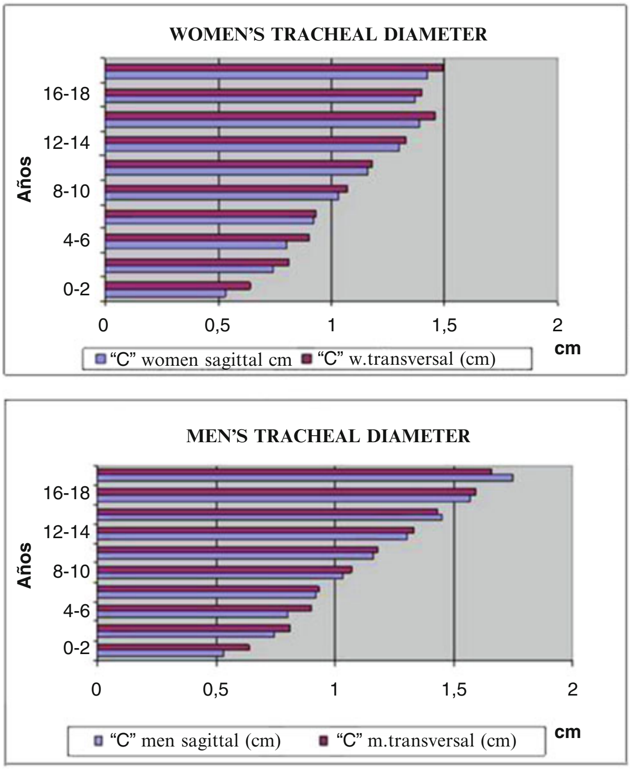
Internal Morphology

The tracheal tube has two covers or layers.

Main, Fibrochondro Elastic Layer

It is a completely circular, soft, and elastic connective tissue fundamental matrix. It affects the entire circumference of the windpipe, presenting tiny holes that represent the point of vascular entrance or exit to and from inside the trachea.

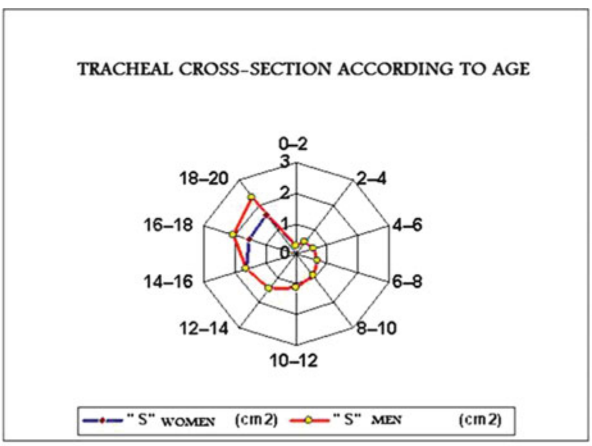
Enclosed to this layer there are bands of incomplete hyaline cartilage rings, horseshoe-shaped. The cartilage forms about four fifths



AGE in years	"C" sagittal women (cm)	"C" transv. women (cm)	"C" sagittal men (cm)	"C" transv. men (cm)
0-2	0.53	0.64	0.53	0.64
2-4	0.74	0.81	0.74	0.81
4-6	0.8	0.9	0.8	0.9
6-8	0.92	0.93	0.92	0.93
8-10	1.03	1.07	1.03	1.07
10-12	1.16	1.18	1.16	1.18
12-14	1.3	1.33	1.3	1.33
14-16	1,39	1,46	1,45	1,43
16-18	1,37	1,4	1,57	1,59
18-20	1,42	1,49	1,75	1,66

Medium tracheal diameter increase similarly in both genders until the age of 14. After that it only increases in men.

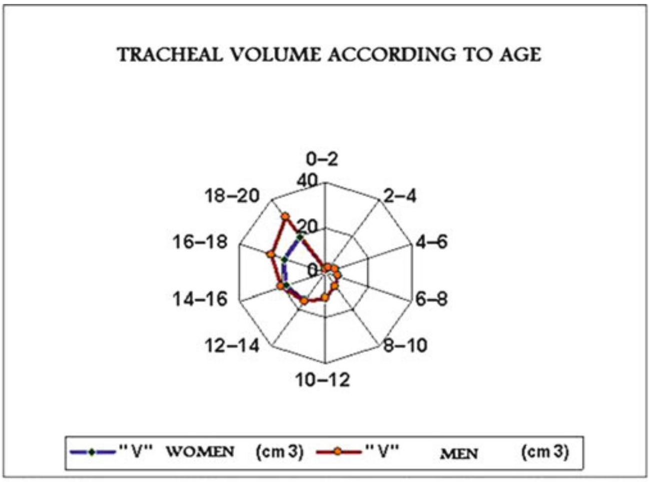
Fig. 1.3 Medium tracheal diameter increases similarly in both genders until the age of 14. After that, it only increases in men



AGE	"S" WOMEN (cm^2)	"S" MEN (cm^2)
0–2	0.28	0.28
2–4	0.48	0.48
4–6	0.58	0.58
6–8	0.69	0.69
8–10	0.89	0.89
10–12	1.1	1.1
12–14	1.39	1.39
14–16	1.62	1.62
16–18	1,54	2,01
18–20	1,59	2,3

- Medium tracheal area increases similarly in both genders until the age of 14.
- At age 20, tracheal area is 44.6% larger in men than in women.

Fig. 1.4 Medium tracheal area increases similarly in both genders until the age of 14. At age 20, tracheal area is 44.6% larger in men than in women



AGE	"V" WOMEN (cm³)	"V" MEN (cm³)
0–2	1.57	1.57
2–4	3.11	3.11
4–6	4.16	4.16
6–8	5.67	5.67
8–10	7.87	7.87
10–12	11.1	11.1
12–14	15.4	15.4
14–16	18,2	20,2
16–18	18,8	25,1
18–20	18,9	30,3

- **Medium tracheal volumen increases similarly in both genders until the age of 14**
- **By age 20, men's tracheal volume is 60% larger than women's.**

Fig. 1.5 Medium tracheal volume increases similarly in both genders until the age of 14. By age 20, men's tracheal volume is 60% larger than women's

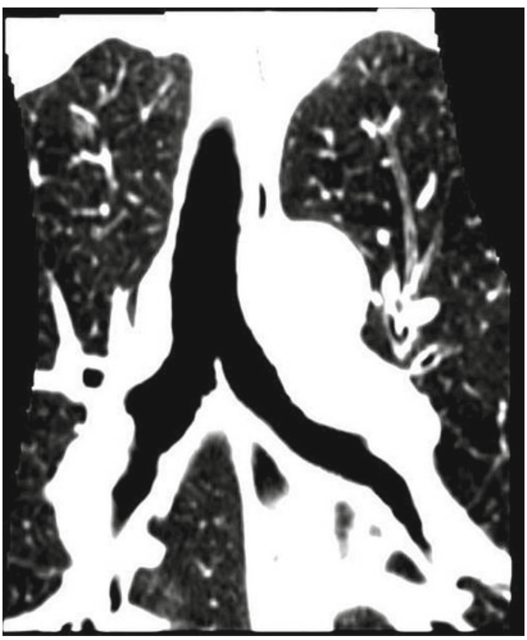


Fig. 1.6 At age 20, men's sagittal and transverse tracheal axes are 23% and 11.4% larger than women's, respectively. Coronal computerized tomography: view of mediastinal trachea, tracheobronchial bifurcation, and main bronchi

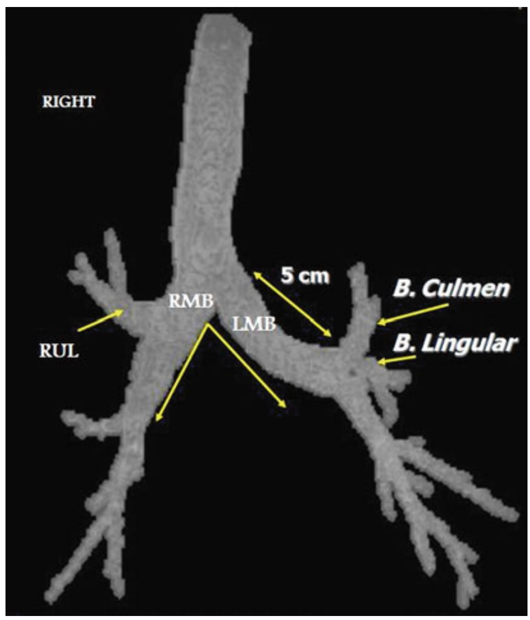


Fig. 1.7 Medium tracheal diameter is 1.5 mm larger in men than in women. Medium bronchial diameter is 1 mm larger in men. 2D tomographic reconstruction of the tracheobronchial tree. Note that the intra-carinal angle is 60°. Lengths are 5 cm for the LMB and 2.5 cm for the RMB

of the circumference of the trachea. Given that the posterior border of the trachea is formed by a fibromuscular membrane, tracheal cross-sectional shape is similar to a letter D, with the flat side located posteriorly. These are known as the tracheal muscles and have vegetative involuntary innervation. The tracheal muscles cross transversely and obliquely, forming a continuous of entangled fibers which constitute a large muscle: the common tracheal muscle. Contraction of this muscle produces adduction of the free cartilage edges, thus modulating the internal tracheal caliber. Wrapping the outer tracheal tube, we found the adventitia, a membrane that acts as a false pretracheal fascia. Between the adventitia and the tracheal wall, vascular and nervous branches are located, and they incorporate to the tracheal tube wall at the level of the interchondral spaces.

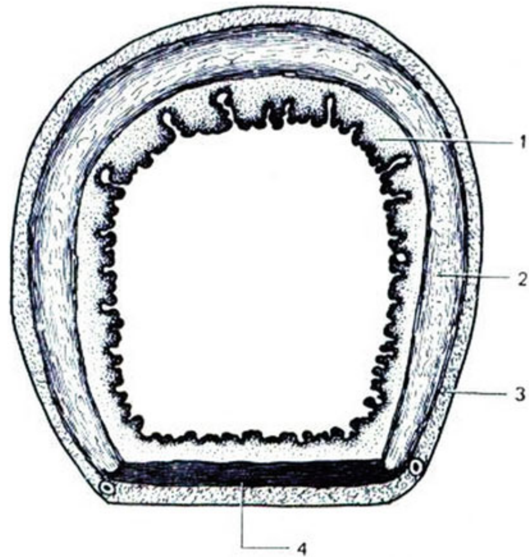


Fig. 1.8 Cross section, trachea: (*1*) respiratory cylindrical epithelium and mucous glands; (*2*) horseshoe-shaped cartilage, with a posterior opening; (*3*) main layer, connective tissue fundamental matrix, surrounded by the adventitia; and (*4*) pars membranosa

Mucous Layer

The trachea is lined by pseudostratified columnar epithelium that sits in an elastic *lamina propria* and covers the inside of the tracheal tube. Goblet mucous cells and small subepithelial glands that secrete into the luminal surface are interspersed among the ciliated columnar cells. The produced mucous adheres to inhaled foreign particles, which are then expelled by the action of cilia propelling the mucous lining upward towards the pharynx from which they can be coughed and sneezed out of the airway. At the end of the tracheal duct, when it is divided into the main bronchi, the mucosa presents a middle line elevation known as carina, similar to a medial ridge. The tracheal carina indicates the entrance to the right and left main bronchus (LMB) (Fig. 1.8a–c).

Blood Supply

Arterial: It is established by two arterial systems on each side of the trachea, communicating the aortic artery with the subclavian artery:

– From the aorta, the left paratracheal ascending artery (Demel arteries) and the tracheobronchial esophageal artery. Of the latter, the right bronchial artery, the esophageal artery, and the right paratracheal ascending artery are born.
– From both subclavian arteries: inferior thyroid arteries and from these in turn emerge the right and left paratracheal descending arteries (Haller arteries).

Each paratracheal descending artery anastomoses with the paratracheal ascending artery of the corresponding side, closing the vascular circuit at the back of the tracheal wall and along its side edges. From these two vascular axes, tracheal perforating arteries are born that supply tracheal layers entering through the interchondral spaces.

Anatomo-Clinical Relationships

The trachea is related to their surroundings through the peri-tracheal fascia, as if it were a hanger between the neck and the mediastinum. Vascular and nerve structures hung from or are in contact with it.

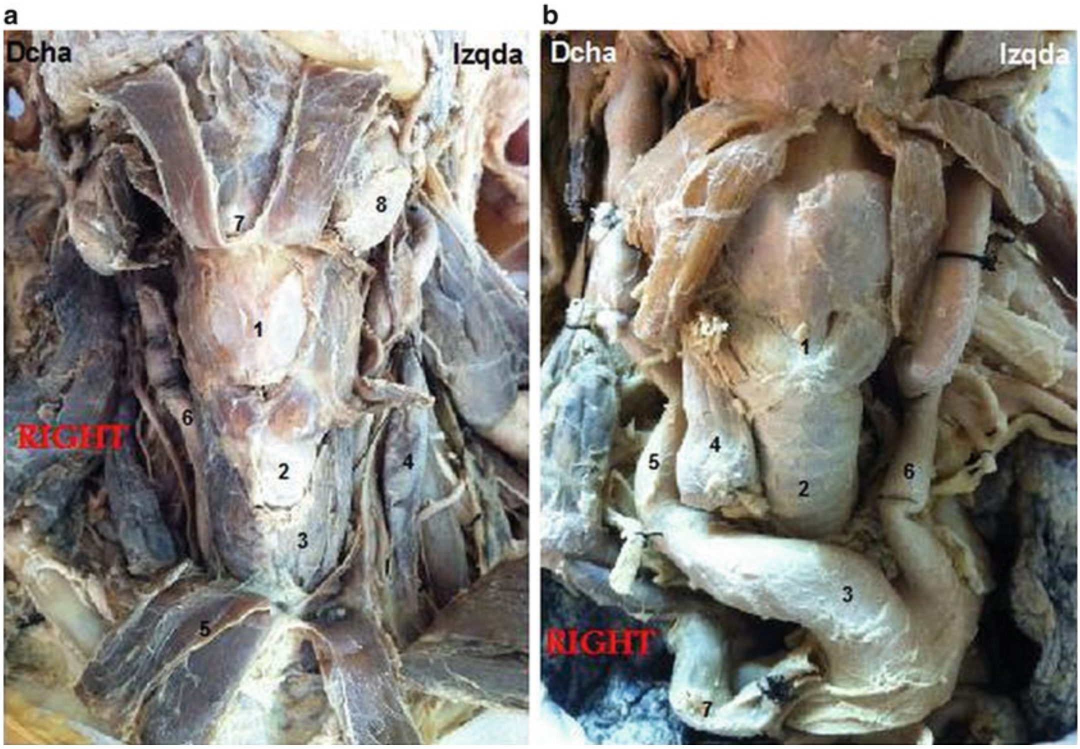


Fig. 1.9 (**a**) Dissection of the cervical trachea: (*1*) larynx, (*2*) trachea, (*3*) left thyroid lobe, (*4*) left internal jugular vein, (*5*) right infrahyoid muscles, (*6*) right common carotid artery, (*7*) hyoid bone, and (*8*) left submandibular gland. (**b**) Dissection of the cervical trachea: (*1*) larynx, (*2*) trachea, (*3*) brachiocephalic arterial trunk, (*4*) right internal jugular vein, (*5*) right common carotid artery, (*6*) left common carotid artery, and (*7*) left venous brachiocephalic trunk or innominate trunk. Unit of Human Anatomy and Embryology. Department of Pathology and Experimental Therapeutics. Universitat de Barcelona

Tracheal relationships from inside out are:

- Posterior: recurrent nerve, esophagus, and vertebral bodies covered by the deep cervical aponeurosis
- Anterior: thyroid gland, medium cervical aponeurosis, anterior jugular veins, and superficial cervical aponeurosis
- Lateral: thyroid gland, vessels and nerves, deep cervical aponeurosis, and superficial cervical aponeurosis (involving the sternocleidomastoid and trapezius muscles) (Fig. 1.9a, b)

The tracheobronchial bifurcation has similar topographical relationships in both genders, and it is located at 7 cm depth from the skin of the anterior midline chest (Figs. 1.10 and 1.11).

Bronchi

Main Bronchi

Main bronchi are located in a compartment known as the mediastinum. The mediastinum is delimited by the pleural cavity. This space does not have a regular shape (mediastinum—"servant" or "heart and major vessels service area"). There are two main bronchi, left and right. Each main bronchus is related to some elements of the mediastinum, and they are not equal in length or size.

LMB: It is 5 cm in length. It is longer than the right main bronchus (RMB), passing beneath the aortic arch and the left pulmonary artery.

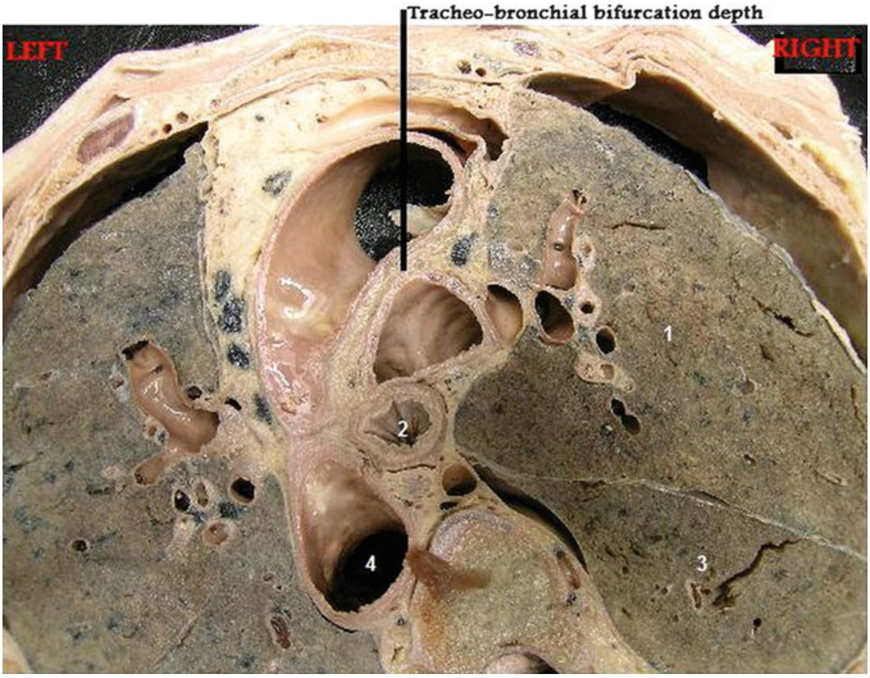


Fig. 1.10 Cranial view of thoracic cross section at the level of D4. Note the location of the tracheobronchial bifurcation at a depth of 7 cm from the surface. (*1*) Right upper lobe, (*2*) thoracic esophagus, (*3*) right lower lobe, (*4*) descending thoracic aorta. Unit of Human Anatomy and Embryology. Department of Pathology and Experimental Therapeutics. Universitat de Barcelona

RMB: It is 2.5 cm in length. It presents more vertical than the left bronchus and has a bigger diameter.

Inside the lung parenchyma, both bronchi will continue dividing into branches to the 24th order (Fig. 1.12).

Bronchial Division

Left Main Bronchus

- Left upper lobe bronchus—it divides into:
  - *Apicoposterior segmental bronchus (B1+2)*, from where B1 (apical) and B2 (dorsal or posterior) bronchi are born
  - *Anterior or ventral segmental bronchus (B3)*
  - *Lingular bronchus*, divided into *superior lingular segmental bronchus (B4)* and *inferior lingular segmental bronchus (B5)*
- Left lower lobe bronchus—it divides into:
  - Apical segmental bronchus form the left lower lobe or Nelson's bronchus (B6)
  - Posterior or dorsal bronchus(B10)
  - Lateral bronchus (B9)
  - Trunk (B7+8) or ventromedial bronchus, from which B7 (medial) and B8 (ventral) originate

Right Main Bronchus

- Right upper lobe bronchus—it divides into:
  - Apical segmental bronchus (B1)
  - Anterior or ventral segmental bronchus(B3)
  - Dorsal segmental bronchus (B2)
- Right middle lobe bronchus—it divides into:
  - Medial segmental bronchus (B5)
  - Lateral segmental bronchus (B4)
- Right lower lobe bronchus—it divides into:
  - Apical bronchus of the right lower lobe (Nelson's bronchus) (B6)
  - Posterior or dorsal bronchus (B10)
  - Lateral bronchus (B9)
  - Anterior bronchus(B8)
  - Paramediastinic bronchus (B7)

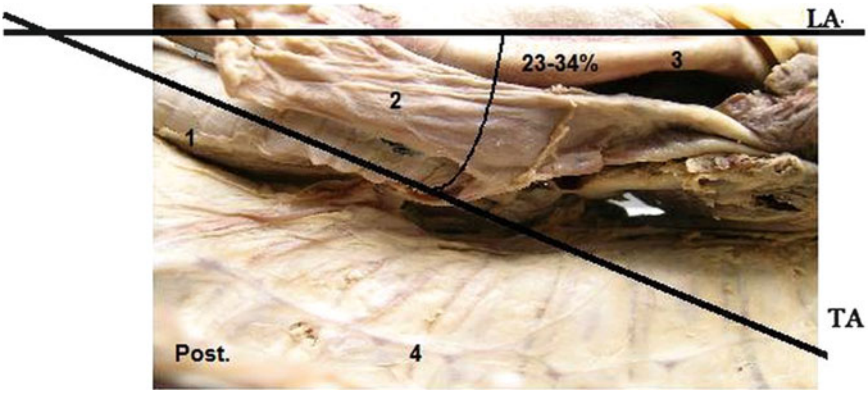


Fig. 1.11 Right lateral view of mediastinum: *TA* tracheal axis, *LA* long axis of the body. (*1*) Trachea, (*2*) superior vena cava, (*3*) ascending aorta, and (*4*) dorsal spine. Unit of Human Anatomy and Embryology. Department of Pathology and Experimental Therapeutics. Universitat de Barcelona

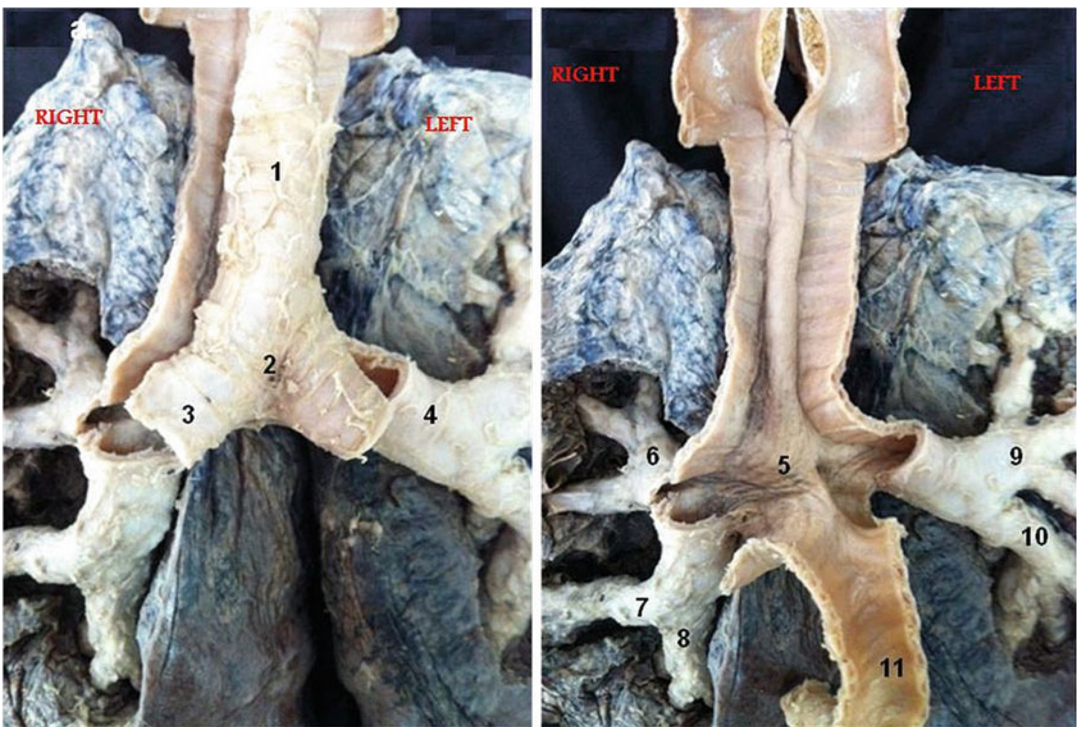


Fig. 1.12 Tracheobronchial bifurcation. Notice in the image on the right a tracheal cross section with anterior inclination of its ventral side. (*1*): Trachea, (*2*) tracheobronchial bifurcation, (*3*) right main bronchus, (*4*) left main bronchus, (*5*) bronchial carina, (*6*) right upper lobe bronchus, (*7*) right middle lobe bronchus, (*8*) right lower lobe bronchus, (*9*) left upper lobe bronchus, (*10*) left lower lobe bronchus, and (*11*) inner wall of the anterior trachea. Unit of Human Anatomy and Embryology. Department of Pathology and Experimental Therapeutics. Universitat de Barcelona

The RMB, after the superior lobe bronchus departure, is called intermedius bronchus. The intermedius bronchus after approximately 15 mm originates the right middle lobe bronchus. From that on, it is called right lower lobe bronchus.

Each bronchial division is accompanied by the corresponding segmental pulmonary artery, giving place to the different bronchopulmonary segments.

Blood Supply

Bronchial arterial supply depends upon the bronchial arteries, which are aortic branches. These bronchial arteries are small in size and are located at the posterior wall of the bronchus following the first bronchial divisions. Bronchial arteries can be divided into:

– Right bronchial artery
– Left superior bronchial artery
– Left inferior bronchial artery

We can also see the Demel artery and the tracheobroncho-esophageal artery, both aortic branches. The latter will divide into three more branches:

- *Ascending tracheal artery*.
- *Esophageal artery*.
- *Right bronchial artery:* It is a single artery located at the posterior bronchial wall that will be divided into two bronchial branches each time it finds a bronchial division.

There are anastomoses between arteries on each side, which close the territory between the left and right bronchial arteries. These interbronchial anastomoses are called *Juttin asa*.

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Flexible Bronchoscopy

2

Alicia N. Rodriguez

Introduction

Flexible Bronchoscopy (FB) is the most common form of bronchoscopy, term that refers to the direct visualization of the airway with diagnostic or therapeutic purposes.

It was Shigeto Ikeda, of Tokyo Japan, who introduced the first flexible fiberoptic bronchoscope in Copenhagen in 1966 [1] (Fig. 2.1). However, the interest on reviewing the airway goes back to 1823, when Horace Green introduced first a sponge and then a rubber catheter into the bronchi, applying silver nitrate to burn lesions located at the level of the larynx and trachea. Later, Joseph O'Dwyer introduced a tube to release adhesions of the lower airways caused by diphtheria, and he also constructed a thin-walled tube to assist in the removal of foreign bodies. In 1897, Gustav Killian in Freiburg, Germany, investigated the larynx and trachea using a laryngoscope designed by Kirstein. During the same year, using an esophagoscope, he removed a pork bone from the airway of a farmer. He then presented his experience in Heidelberg, naming it "direct bronchoscopy," becoming the Father of Bronchoscopy [2].

At the same time in the US, Chevalier Jackson developed an esophagoscope, and built a smaller version to retrieve a coin from a child's airway. He practiced his skills on esophagus and larynxes of dogs and human cadavers. He also initiated the first laryngoscopy class at West Medical College, developing safety protocols and a systematic training to avoid adverse results of the technique when applied by untrained physicians. During 1904, he developed a bronchoscope with a light on its tip, designing an additional light source and a drainage tube. He also built and perfectioned several ancillary instruments and was able to perform rigid bronchoscopy reporting a procedure related death of less than 1% [3].

During more than 70 years, the rigid bronchoscope or open tube was the only available instrument to review the airway. At first, it was mainly used to remove foreign bodies or dilate strictures, but later new applications were described: aspiration of secretions, hemoptysis treatment, biopsies, etc.

As time passed, many other achievements such as the appearance of telescopes for magnification, and photography to document images became available, and along with the practical application of the optical properties of glass fibers, described by John Tyndall in 1870, provided a favorable field to the development of the flexible bronchoscope as we know it today [2, 3].

The arrival of the FB represented a huge shift in the endoscopic practice; soon it was evident that the procedure was easier to perform than rigid bronchoscopy and it allowed a better

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J.P. Díaz-Jimenez and A.N. Rodriguez (eds.), *Interventions in Pulmonary Medicine*,
DOI 10.1007/978-1-4614-6009-1_2, © Springer Science+Business Media New York 2013