Anatomy of the Trachea

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KEYWORDS

• Tracheal anatomy • Tracheal embryology • Endobronchial anatomy

KEY POINTS

- The trachea is a 10-to-13-cm semi-rigid tubular organ that begins at the inferior aspect of the cricoid cartilage and ends at the carinal bifurcation into the right and left mainstem bronchi.
- The development of the trachea and respiratory system begins at approximately 4 weeks in utero and continues into antenatal life.
- Tracheal blood supply is segmental, potentially variable, and dependent on surrounding anatomy.
- The combination of bronchoscopy and high-resolution computed tomography with inspiratory and expiratory phases remains the best test for defining the anatomy of the trachea and surrounding structures.

INTRODUCTION

The purpose of this article is to provide a review of tracheal anatomy. Included is a summary of tracheal embryology, tracheal structure and histology, arterial and venous blood supply, lymphatic drainage, and the relationships between the trachea and surrounding viscera. Endobronchial tracheal anatomy and contemporary tracheal imaging techniques are also discussed. The goal is to provide surgeons with a detailed understanding of tracheal anatomy to aid in the diagnosis and operative management of intrinsic and extrinsic tracheal disease.

EMBRYOLOGY AND HISTOLOGY

The development of the respiratory system begins at approximately 4 weeks in utero.[1] At that time, an outpouching forms from the ventral wall of the foregut at the laryngotracheal orifice. This respiratory diverticulum initially exists in continuity with the foregut, but as it develops caudally 2 tracheoesophageal ridges form and subsequently fuse into the tracheoesophageal septum separating the ventral trachea from the dorsal esophagus. The aerodigestive cavities (ie, antenatal larynx and pharynx) remain in communication cephelad at the laryngotracheal orifice.

The larynx, trachea, bronchi, and distal airways are lined by epithelium and glandular tissue derived from the endoderm, while the structural components of cartilage and muscle are derived from the splanchnic mesoderm of the fourth and sixth pharyngeal arches. The cartilaginous structure of the larynx and trachea—the epiglottis, thyroid, cricoid, and arytenoid cartilages—are also derived from the fourth and sixth pharyngeal arches. The lumen of the larynx is temporarily occluded and subsequently recanalizes with the formation of the laryngeal ventricles, as well as the true and false vocal folds. The cartilaginous rings of the trachea develop at approximately 10 weeks in utero.

At approximately 5 weeks in utero, the ventral respiratory diverticulum divides into 2 additional diverticula, or right and left bronchial buds, which develop caudally and laterally into the right and left mainstem bronchi. Subsequent divisions of each mainstem bronchus continue through 24 weeks in utero forming the segmental anatomy of the lung. Like the upper airway, the lower airway

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mucosa is composed of ciliated pseudostratified columnar epithelium, basement membrane, and lamina propria. Interspersed among the epithelium are goblet cells, which produce mucin that, along with the cilia, aids in the sequestration and clearance of inhaled pathogens. Deep to the mucosa are the submucosa, hyaline cartilage, and additional glands that produce fluid to humidify air during inhalation (Fig. 1).[2] The development and maturation of the alveoli, pulmonary vasculature, pneumocytes, and gas-exchange apparatus occur through the remainder of gestation and the antenatal period. The details of this development are beyond the scope of this article.

The result of this embryologic development is a respiratory system that serves the following fundamental purposes:

1. Conduit for inspiration and expiration of air;
2. Structural and functional apparatus for phonation;
3. Mucociliary escalator for airway clearance and pulmonary defense;
4. Exchange of oxygen and carbon dioxide.

The remainder of this article will focus on the surgical anatomy of the trachea and surrounding structures.

Fig. 1. Histology of the human trachea. Cross-section of the trachea showing the following layers of tracheal wall beginning from the tracheal lumen: lamina propria (lp), submucosa (sm), salivary glands (sl), cartilage of tracheal ring (trc), and investing adventitia (ta), muscle (*). (Bertalan Dudás, Chapter 8 - Respiratory System, Editor(s): Bertalan Dudás, Human Histology, Academic Press, 2023, Pages 190-211.)

ANATOMY

Structural Anatomy of the Trachea and Surrounding Structures

The adult trachea is a semi-rigid tubular organ that begins cephalad at the inferior aspect of the cricoid cartilage at approximately the sixth cervical vertebral body.[3] Caudally, the trachea ends at the carinal bifurcation into the right and left mainstem bronchi. This is located at the level between the fourth and fifth thoracic vertebral bodies. In infants, the trachea is approximately 5 to 6 cm in length and reaches length of 10 to 13 cm in adulthood.[4] These lengths vary with the changes in transtracheal pressure during inspiration and expiration. In patients with minimal soft tissue in the neck, the location of the airway can be felt by palpating the cricothyroid membrane, cricoid cartilage, and first 2 to 3 tracheal rings along approximately 5 cm of trachea above the sternal notch. The distance between the cricoid cartilage and first tracheal can be small making palpation of the first tracheal ring challenging. Despite its semi-rigid structure and surrounding soft tissue attachments, simple neck extension results in several additional centimeters of the trachea to be palpated above the sternal notch, in part due to tracheal lengthening.[5] Likewise, cervical spinal pathology (eg, scoliosis, kyphosis) may result in a shorter proximal segment of the trachea above the sternal notch. As such, in infancy, the trachea is relatively vertically oriented and with increasing age becomes more horizontally oriented with progressive cervical kyphosis.[6] These are important considerations when deciding on optimal surgical approach to the airway, especially mid-to-distal tracheal pathology where transcervical, transsternal, or right posterolateral transthoracic approaches may be employed. The distal trachea travels posteriorly as it passes behind the sternum and visceral mediastinal structures. The carina is approximately at the level of the sternomanubrial junction or second thoracic rib anteriorly.

In axial cross section through the mid-trachea, the trachea has a D-shape with an anterior C-shaped cartilaginous ring and posterior membranous wall. Along the membranous wall is the trachealis muscle, derived from the embryologic tracheoesophageal septum, in close apposition to the anterior wall of the esophagus. In neonates and infants, the proximal trachea is larger in diameter compared with the mid-trachea and distal trachea, creating a funnel-shape from the larynx to the mid-trachea.[4,7] Over time, this shape changes to create a more uniform cylindrical tube along the length of the trachea. The inner diameter of the adult trachea is approximately 2.1 to 2.7 cm based on measurements of the airway on non-dynamic radiography and computed tomography images. It should be noted that the inner diameter is dependent on body surface area, sex, and trans-tracheal pressure gradients during inspiration and expiration.[8–12]

In total along the length of the trachea, there are approximately 18 incomplete, C-shaped, cartilaginous rings. Each tracheal ring is approximately 4 mm in height, allowing for a rough approximation of 2 tracheal rings per centimeter of tracheal length. The tracheal rings are connected by a dynamic intercartilaginous membrane. This membrane also contributes, in part, to the variation in tracheal length during extension and ventilation. Like costochondral cartilage in the thorax, the cartilage of the tracheal rings is subject to age and pathophysiologic changes. Over time, tracheal rings may become stiff or form calcifications, leading to a loss of compliance and increased fragility.[4] In patients with smoking-related chronic bronchitis or chronic obstructive pulmonary disease, persistent and recurrent inflammation from inhaled toxins may lead to softening of the tracheal rings and subsequent tracheomalacia.

Along the anterior surface of the cephalad trachea overlies the thyroid gland with the thyroid isthmus located at the level of the second tracheal ring.[13] Two of the infrahyoid muscles, the thyrohyoid and sternothyroid muscles, anchor the thyroid cartilage to the hyoid and manubrium of the sternum, respectively. At the level of the thoracic inlet, the brachiocephalic trunk, or innominate artery, crosses from left to right anteriorly over the trachea. More caudally, just proximal to the level of the carinal bifurcation, the right pulmonary artery courses from left to right as it travels anterior to the right mainstem bronchus.[14] Posteriorly, given the embryologic development described previously, the esophagus remains in close approximation to the trachea, separated from the trachealis muscle by a thin layer of connective tissue. As the trachea and esophagus pass caudally into the thorax, the esophagus may begin to course leftward. Laterally, in the tracheoesophageal groove lies the recurrent laryngeal nerves; their detailed anatomy will be discussed in subsequent sections. Distally, to the left of the trachea is the aortic arch. The left mainstem bronchus travels beneath the aortic arch. On the right, the mediastinal pleura and azygous vein closely abut the trachea. These relationships between the trachea to surrounding structures are of particular importance to surgeons when diagnosing extrinsic tracheal pathology (eg, invasive thyroid cancer, tracheoesophageal fistulae, vascular rings) and operatively mobilizing the trachea as in tracheal resections or cervical mediastinoscopy (Fig. 2).

Arterial Blood Supply

The macrovasculature to the trachea is segmental with differential arterial blood supply to the cervical and thoracic segments of the trachea contributing to a rich collateral microvascular structure at the level of the tracheal wall. This was first demonstrated in a study by Miura and Grillo at Massachusetts General Hospital in 1966 and subsequently by Salassa, Pearson, and Payne at Mayo Clinic in 1977.[6,15,16] In the latter report, the authors presented the gross and microscopic arterial anatomy supplying the trachea following the post-mortem dissection of 21 laryngotracheal specimens. The cervical tracheal is supplied primarily from the inferior thyroid artery. The right and left subclavian arteries give rise to the thyrocervical trunk, typically as a third branch following the vertebral and internal thoracic arteries within the first segment of the subclavian arteries. The inferior thyroid artery is one of the branches of the thyrocervical trunk, from which there are typically 3 branches to the cervical trachea and esophagus. These branches travel cephalad and

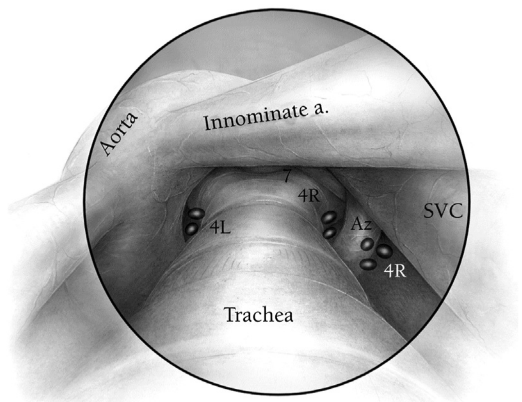

Fig. 2. Relationship of the trachea to surrounding structures. Illustration of the anterior trachea and surrounding vascular structures and lymph node basins during cervical mediastinoscopy. Anterior to the trachea at thoracic inlet is the innominate artery. Distally, the trachea is anchored on the left by the aortic arch. To the right are the superior vena cava, azygos vein wrapping around the right mainstem bronchus, and mediastinal pleura. Right (4R) and left (4L) paratracheal lymph node stations are shown, as well as the subcarinal (7) lymph node station. (*Data from* Mentzer SJ. Mediastinal staging prior to surgical resection. *Oper Tech Thorac Cardiovasc Surg*. 2005;10(2):152-165. https://doi.org/10.1053/j.optechstcvs.2005.06.001.)

medially posterior to the carotid sheath and enter the region of the tracheoesophageal groove laterally. All branches contribute in some way to the blood supply of the trachea. The first branch is most caudal and predominantly supplies the trachea, while the second and third more cephalad branches preferentially supply the esophagus and thyroid gland, respectively. The third branch forms a collateral network with branches of the superior thyroid artery, which is typically the first branch of the external carotid artery (**Fig. 3**A, B).

The blood supply to the cephalad thoracic trachea is variable and derived from the innominate artery or subclavian arteries, including direct branches of the supreme intercostal artery and internal thoracic artery branches (see **Fig. 3**A, B).[17] The distal trachea, carina, and right and left mainstem bronchi are consistently supplied from the bronchial arteries from the aorta at the level of the sixth thoracic vertebra. There is a great degree of variability to the bronchial artery anatomy, but the most common pattern in 40% of patients is 1 right and 2 left bronchial arteries.[17,18] The right, cephalad most bronchial artery originates on the anteromedial surface of the thoracic aorta, which has early anterior and posterior branches. The anterior branch travels anterior to and supplies the left mainstem bronchus and carina. The posterior branch courses posterior to the thoracic esophagus and supplies the right mainstem bronchus. The 2 left bronchial arteries originate more caudally from the thoracic aorta and supply the carina and left mainstem bronchus (**Fig. 4**).

At the level of the tracheal wall, the gross blood supply to the trachea forms a rich network of microvasculature. In the cervical trachea, each of the 3 inferior thyroid artery branches approaches the trachea laterally within the tracheoesophageal groove. These branches give rise to an anterior

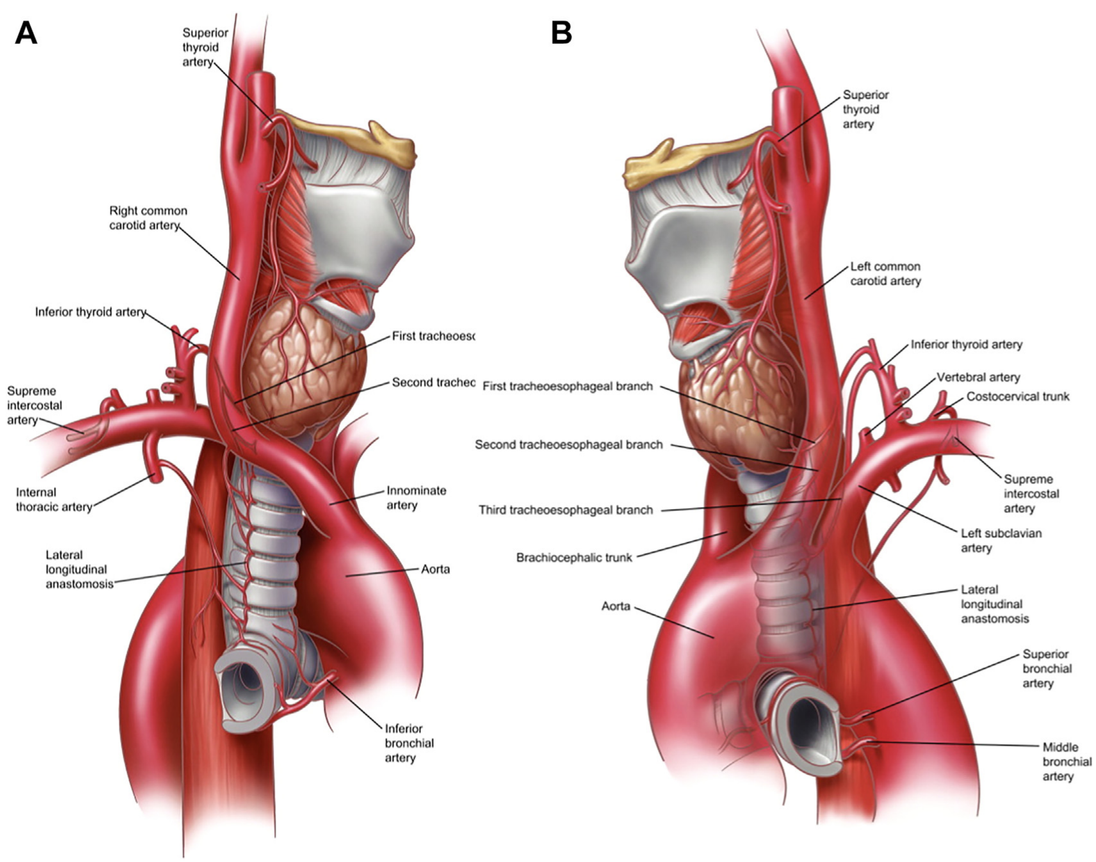

Fig. 3. Tracheal blood supply. Right (*A*) and left (*B*) lateral views of tracheal blood supply. Note segmental blood supply with branches of the inferior thyroid artery supplying the cervical trachea; direct innominate, internal thoracic, or supreme intercostal arteries supplying the proximal thoracic trachea; and bronchial arteries supplying to distal thoracic trachea, carina, and mainstem bronchi. (*Data from* Minnich DJ, Mathisen DJ. Anatomy of the Trachea, Carina, and Bronchi. *Thorac Surg Clin Thorac Anatomy, Part 1 Chest Wall, Airway, Lungs*. 2007;17(4):575-585.)

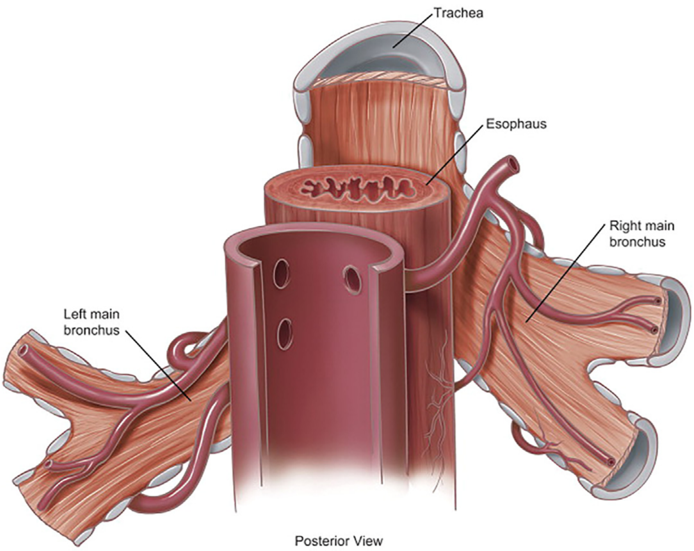

Fig. 4. Blood supply to the distal trachea and carina. Posterior view of bronchial most conventional pattern of bronchial arterial branching from the thoracic aorta. A single right bronchial artery arises most cephalad and supplies the carina and right mainstem bronchus. The 2 more caudal bronchial arteries supply the left tracheobronchial tree. (*Data from* Riquet M. Bronchial Arteries and Lymphatics of the Lung. *Thorac Surg Clin Thorac Anatomy, Part 1 Chest Wall, Airway, Lungs*. 2007;17(4):619–638.)

tracheal branch and posterior esophageal branch. The anterior branch subsequently divides into small branches that enter the tracheal wall anterior to the interface of the tracheal cartilage and membranous wall. The posterior esophageal branch provides a small arterial feeder vessel to the membranous wall of the trachea before terminating in the esophageal wall (**Fig. 5**).

The anterior tracheal branches span approximately 1.0 to 1.5 cm of tracheal length and contribute to a lateral longitudinal anastomosis with collateral branches from the arterial branches above and below. From this lateral longitudinal network, transverse intercartilagenous arteries supply each space between tracheal rings, running both anteriorly within the tracheal wall toward the midline and posteriorly to the interface of the tracheal cartilage and membranous wall. These branches, along with the arterial feeder vessels to the membranous wall, give risk to a rich capillary network within the submucosal layer of the tracheal wall (see **Fig. 6**).

Understanding these elements of the trachea's macrovascular and microvascular arterial supply is critical for surgeons when performing tracheal resections. For example, during a tracheal resection and reconstruction, the surgeon must limit the length of tracheal dissection cephalad and caudad to the location of pathology to preserve the arterial contributions to the lateral longitudinal anastomosis. Similarly, when circumferentially dissecting the trachea, the surgeon must carry out the dissection along the wall of the trachea to preserve the remainder of the lateral vascular pedicles to the airway.

Venous Drainage and Lymphatics

The venous drainage of the trachea is not as clearly defined as the arterial supply. The distal larynx and proximal cervical trachea venous drainage is through laryngeal and inferior thyroid veins, which ultimately drain into the jugular and brachiocephalic veins. The thoracic trachea and bronchi's venous drainage is through the superficial bronchial venous system, which drains into the azygos, hemiazygos, and pulmonary veins. The lymphatic drainage of the trachea includes deep cervical, upper paratracheal, lower paratracheal, and subcarinal lymph nodes. In addition, there are longitudinal paratracheal lymphatic collectors that run along the lateral borders of the trachea between these lymph node stations. On the right, the paratracheal collectors terminate at the confluence of the right internal jugular and subclavian veins. On the left, the paratracheal collectors drain into the thoracic duct or directly at the confluence of left internal jugular and subclavian veins.[18]

Innervation and Surrounding Nerves

Branches of the vagus nerves provide the motor and sensory innervation to the trachea. Cephalad near the base of the skull, the superior laryngeal nerve originates from the vagus nerve. It courses along the medial surface of the internal carotid artery giving rise to the internal and external branches of the superior laryngeal nerve. The internal branch provides only sensory innervation to the structures above and including the vocal folds. The external branch travels with the superior thyroid artery and

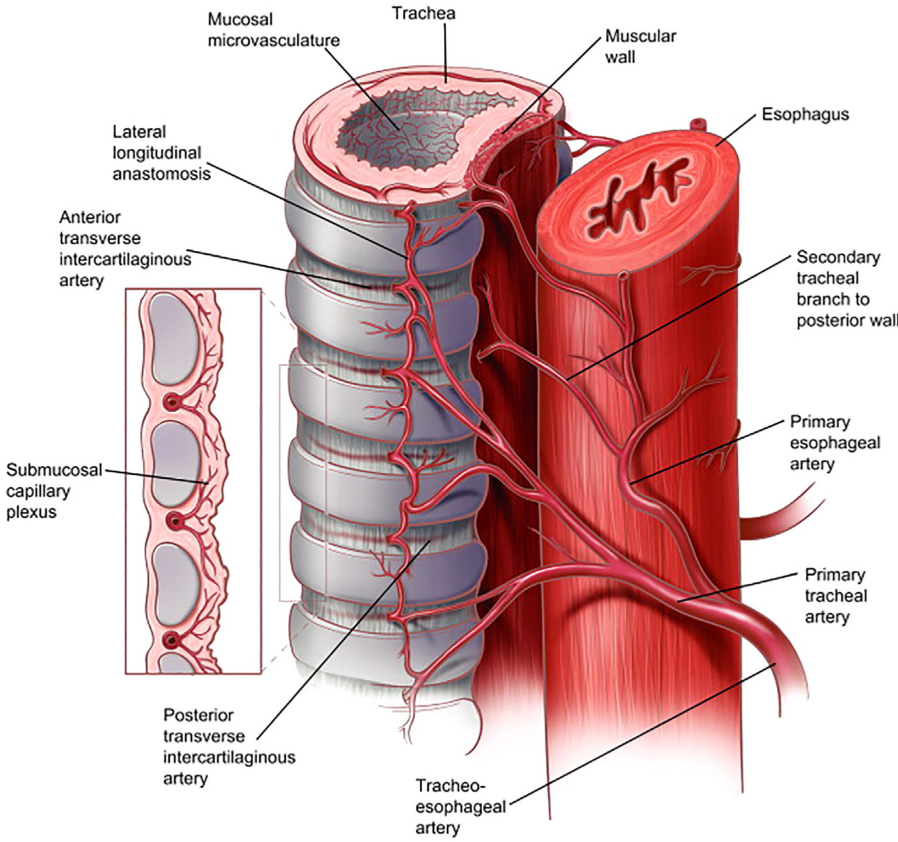

Fig. 5. Microvascular tracheal blood supply. Posterolateral view of cervical and proximal thoracic trachea's terminal blood supply and microvasculature. (*Data from* Minnich DJ, Mathisen DJ. Anatomy of the Trachea, Carina, and Bronchi. *Thorac Surg Clin Thorac Anatomy, Part 1 Chest Wall, Airway, Lungs*. 2007;17(4):575-585.)

provides motor innervation to the cricothyroid muscles. The left and right vagus nerves give off recurrent laryngeal nerve branches within the thorax. The left recurrent laryngeal nerve wraps around the aortic arch lateral to the ligamentum arteriosum and travels within the left tracheoesophageal groove. The right recurrent laryngeal nerve wraps around the right subclavian artery and travels laterally to medially before entering the right tracheoesophageal groove (**Fig. 6**). Here, these nerves course with the inferior thyroid artery. Functionally, the recurrent laryngeal nerves provide the sensory innervation to the airway below the level of the vocal folds, as well as motor innervation to all laryngotracheal muscles except the cricothyroid muscles. The nerves continue to travel cephelad and terminate in the larynx.

Radiographic Anatomy

Plain posterior-anterior and lateral chest radiography shows the trachea as a column of vertical air overlapping the spine. The surrounding viscera make detailed tracheal anatomy and the distal airways challenging to define. However, subtle radiographic changes serve as an indicator of tracheal pathology, such tracheal stenosis, an endotracheal mass, or saber-sheath trachea from chronic obstructive pulmonary disease.[19] High-resolution computed tomography with thin cross-sectional images, especially when coupled with bronchoscopy, serves as the best imaging test for delineating the anatomy of the trachea and surrounding structures. At the authors' institution, the dedicated tracheal protocol computed tomography includes imaging of the neck and chest with static, forced inspiratory, and forced expiratory phases (**Fig. 7**). Coordination with an experienced thoracic radiologist allows reformatting of the scans into 3-dimensional images as well as multiplanar processing to acquire estimates of the cross-sectional area of the airway. For functional disorders of the airway, such as tracheomalacia or excessive dynamic airway collapse, or else for patients where radiation or contrast exposure remains a concern, MRI can be used. The authors'

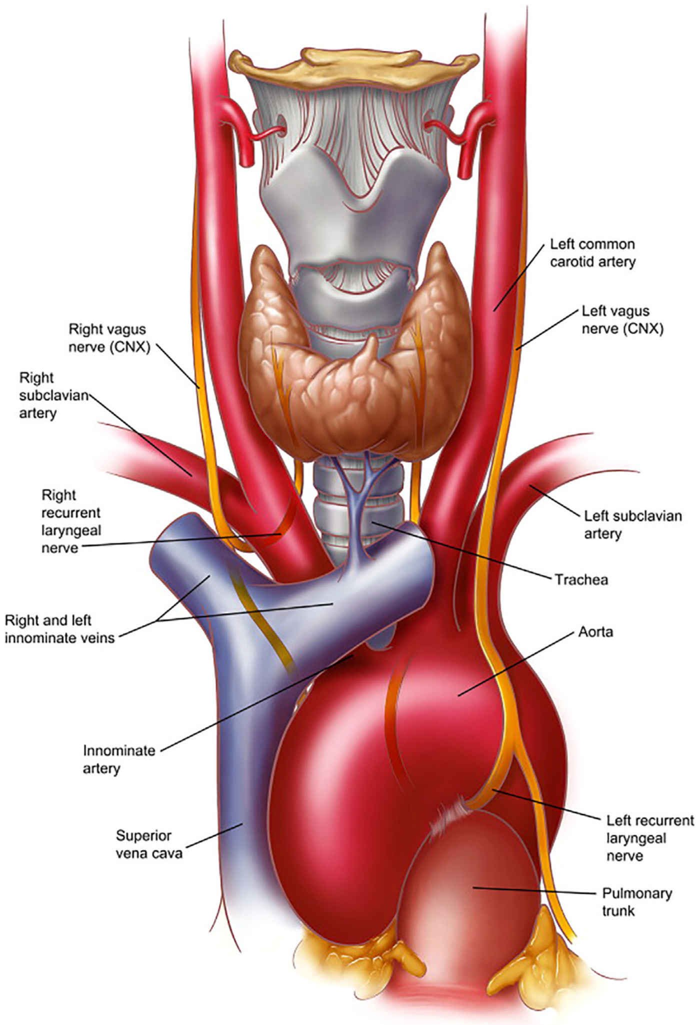

Fig. 6. Vagus and recurrent laryngeal nerve anatomy. Anterior depiction of right and left vagus nerves. The right recurrent laryngeal nerve wraps around the right subclavian artery, whereas the left recurrent laryngeal nerve wraps around the aorta lateral to the ligamentum arteriosum. (*Data from* Minnich DJ, Mathisen DJ. Anatomy of the Trachea, Carina, and Bronchi. *Thorac Surg Clin Thorac Anatomy, Part 1 Chest Wall, Airway, Lungs*. 2007;17(4):575-585.)

MRI protocol allows dynamic imaging not only during forced inspiration and expiration, but also during quiet breathing. This allows images to be captured truly orthogonal to the airway for estimates of airway diameter and collapse.

Endoscopic Anatomy

Intrinsic tracheal pathology is best diagnosed endoscopically with bronchoscopy. As mentioned previously, surface anatomy is palpable and appreciated only within the proximal trachea and may be limited by cervical spine pathology and range of motion. Cross-sectional imaging of the neck and chest for tracheal pathology has been discussed and remains a valuable diagnostic adjunct especially when evaluating the relationship between the airway and surrounding structures. However, these imaging studies are less dynamic and have poor sensitivity for limited mucosal disease or short-segment lesions when compared with bronchoscopy. Bronchoscopy can be performed awake or under minimal sedation to allow for endoscopic airway evaluation during quiet breathing, forced inspiration, forced expiration, or coughing. Careful coordination with an experienced thoracic anesthesiologist is paramount especially in cases for the potential for loss of airway.[20]

Traditionally, rigid bronchoscopy was the primary modality for endoscopic evaluation of the trachea. It remains the gold standard for diagnosis, localization, and potential treatment of tracheal pathology. With improvements in fiberoptic technology and the development of flexible endoscopic instrumentation, however, flexible

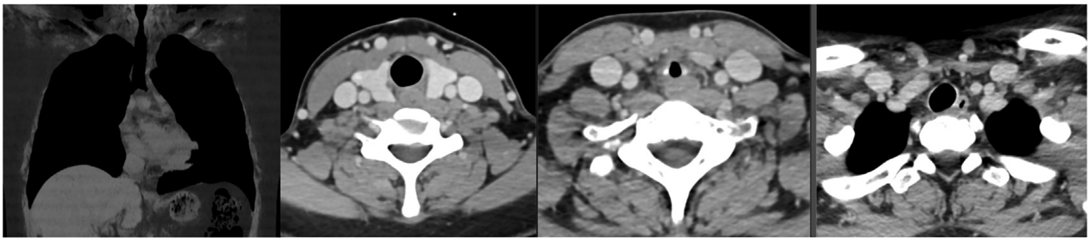

Fig. 7. Tracheal Radiology. Coronal and axial representative images from inspiratory and expiratory phases of chest computed tomography in a patient with acquired post-intubation tracheal stenosis.

bronchoscopy provides the surgeon with sufficient ability to diagnose, localize, and potentially intervene upon most tracheal pathologies. Important anatomic landmarks on bronchoscopy include the following (Fig. 8A–C):

- *Larynx:* Following the base of the tongue into the larynx provides visualization of the epiglottis, arytenoid cartilages, aryepiglottic folds, and vocal folds between 10 and 15 cm from the incisors. Pathology of the proximal airway (eg, subglottic stenosis) can extend proximally to involve the vocal folds and larynx. Under minimal sedation and without paralysis, the vocal folds should also be inspected for function before delivering topical anesthesia.
- *Subglottis:* Distal to the vocal folds at approximately 15 cm from the incisors, the cricothyroid membrane can be appreciated anteriorly, which appears as a subtle anterior recess. The cricoid cartilage is identified by visualizing cartilage along the posterior airway, endoscopically marking the upper boundary of the trachea.
- *Trachea:* Bronchoscopic orientation within the trachea is maintained by positioning the pearly-white appearing cartilage anteriorly and striations of the membranous wall and trachealis muscle posteriorly. Along the length of the trachea are additional landmarks that demonstrate its relationship to surrounding structures. At the level of the thoracic inlet, the innominate artery crosses anteriorly over the trachea, which can be appreciated on bronchoscopy by a transmitted pulsation. Distally, the airway narrows slightly and the carina and proximal right and left mainstem bronchi are visualized. Loss of the sharp angle of the carinal bifurcation is a subtle indicator of potential lymphadenopathy or other subcarinal pathology. Cervical and thoracic esophageal pathology may infiltrate or compress the membranous wall of the trachea or proximal left mainstem bronchus.

When tracheal pathology is identified, it is important to measure not only the length of involved airway, but also the distances between the distal extent of the pathology and carina, as

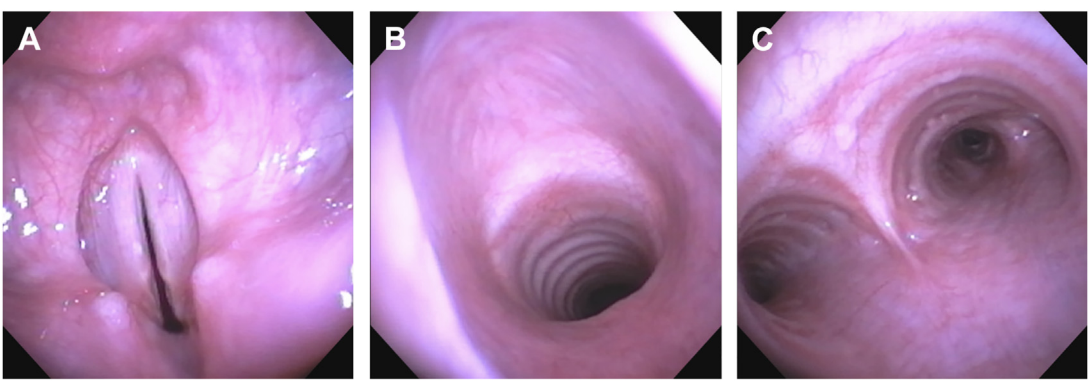

Fig. 8. Endoscopic Airway Anatomy. (*A*) Endoscopic visualization of the larynx, vocal folds, and arytenoid cartilages. (*B*) Subglottis distal to focal folds with endoscopic view of the locations of the thyroid cartilage, cricothyroid membrane (anterior), cricoid cartilage (circumferential cartilagenous ring), and proximal trachea (incomplete cartilagenous rings). (*C*) Sharp carina with bifurcation of the trachea into the right and left mainstem bronchi.

well as the proximal extent of the pathology and the vocal folds. This can be accomplished with both rigid and flexible bronchoscopy. With flexible bronchoscopy, the surgeon first advances the scope to level of the carina and then pinches the bronchoscope between the thumb and fingernail where it is flush with the endotracheal tube. The surgeon then retracts the bronchoscope to the distal extent of the pathology and measures the distance along the bronchoscopy between the endotracheal tube and where the bronchoscope was pinched. This process is repeated from the proximal extent of the pathology to the level of the vocal folds.

CLINICS CARE POINTS

- Understanding tracheal embryology and resultant anatomy allows surgeons to diagnose intrinsic, extrinsic, and both structural and functional disorders of the airway.
- The macrovascular arterial blood supply to the trachea is segmental and variable, forming a rich network of microvascular collaterals within the tracheal wall. Excessive dissection lateral to or along the length of the trachea may result in ischemia.
- Tracheal anatomy can be imaged through plain radiography, computed tomography, and MRI. High-resolution and dynamic protocols for cross-sectional imaging modalities improve their sensitivity and specificity for both structural and functional airway disease.
- Bronchoscopy remains the gold standard for delineating tracheal anatomy and provides surgeons with the ability to perform additional diagnostic and therapeutic interventions.

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DISCLOSURES

The authors have nothing to disclose.

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