Chapter 12: Anatomy of the larynx and tracheobronchial tree

Neil Weir

Development of larynx, trachea, bronchi and lungs

During the fourth week of embryonic development, the rudiment of the respiratory tree appears as a median laryngotracheal groove in the ventral wall of the pharynx. The groove subsequently deepens and its edges fuse to form a septum, thus converting the groove into a splanchnopleuric laryngotracheal tube. This process of fusion commences caudally and extends cranially but does not involve the cranial end where the edges remain separate, bounding a slit-like aperture through which the tube opens into the pharynx.

The tube is lined with endoderm from which the epithelial lining of the respiratory tract is developed. The cranial end of the tube forms the larynx and the trachea, and the caudal end produces two lateral outgrowths from which the bronchi and right and left lung buds develop. These grow into the pleural coelomata and are thus covered with splanchnic mesenchyme from which the connective tissue, cartilage, non-striated muscle and the vasculature of the bronchi and lungs are developed.

Larynx and trachea

The primitive larynx is the cranial end of the laryngotracheal groove, bounded vertically by the caudal part of the hypobranchial eminence and laterally by the ventral folds of the sixth arches. The arytenoid swellings appear on both sides of the groove and as they enlarge they become approximated to each other and to the caudal part of the hypobranchial eminence from which the epiglottis develops. The opening into the laryngeal cavity is at first a vertical slit or cleft, which becomes T-shaped with the appearance of the arytenoids. However, the epithelial walls of the cleft soon adhere to each other and the aperture of the larynx is thus occluded until the third month when its lumen is restored. The arytenoid swellings grow upwards and deepen to produce the primitive aryepiglottic folds. This, in turn, produces a further aperture above the level of the primitive aperture which itself becomes the glottis. During the second month of fetal life, the arytenoid swellings differentiate into the arytenoid and corniculate cartilages (derivatives of the sixth arch), and the folds joining them to the epiglottis become the aryepiglottic folds in which the cuneiform cartilages are developed as derivatives of the epiglottis. The thyroid cartilage develops from the ventral ends of the cartilages of the fourth branchial arch, appearing as two lateral plates, each with two chondrification centres. The cricoid cartilage and cartilages of the trachea develop from the sixth branchial arch during the sixth week. The trachea increases rapidly in length from the fifth week onwards.

The branchial nerves of the fourth and sixth arches, namely the superior laryngeal and recurrent laryngeal nerves, supply the larynx.

Each visceral arch is traversed by an artery (aortic arch). Each aortic arch connects the ventral and dorsal aortae of its own visceral arch. The primitive recurrent laryngeal nerve enters the sixth visceral arch, on each side, caudal to the sixth aortic arch. On the left side, the arch retains its position as the ductus arteriosus and the nerve is found caudal to the
ligamentum arteriosum in the adult. On the right side, the dorsal part of the sixth aortic arch and the whole of the fifth arch disappear. The nerve is, therefore, found on the caudal aspect of the fourth aortic arch, which becomes the subclavian artery.

**Bronchi and lungs**

The right and left lung buds appear before the laryngotracheal groove is converted into a tube. They grow out into the pleural passages caudal to the common cardinal veins and divide into lobules, three appearing on the right and two on the left. It is uncertain whether lung budding determines the septal pattern or whether the development of the connective tissue septa controls the final form of the lung (Emery, 1969). Each primary bronchus continues to divide dichotomously until by birth some 18-23 generations of divisions have appeared which are not necessarily equal in the individual lobes.

Three periods of development of the lung are described: a 'glandular' period, when the primitive bronchi ramify through the mesenchyme (up to 4 months); a 'canicular' period when the primitive respiratory bronchioles are generated from the terminal bronchi (4-6 months); and an 'alveolar' period from 6 months onwards when further respiratory bronchioles and the terminal alveoli, which will be the functional airspaces with their blood-air barriers, are formed.

There has been considerable discussion as to how much of the subsequent development of the bronchi and alveoli occurs after birth. The current views are summarized by Reid (1967) in her three 'laws' of lung development:

1. the bronchial tree is fully developed by the sixteenth week of intrauterine life

2. alveoli, as commonly understood, develop after birth, increasing in number until the age of 8 years, and in size until growth of the chest wall is complete

3. blood vessels are remodelled and increase in number, certainly while new alveoli are forming.

During the course of their development, the lungs migrate in a caudal direction, so that by birth the bifurcation of the trachea is opposite the fourth thoracic vertebra. As the lungs grow, they become enveloped in pleura derived from the splanchnic mesenchyme.

For further reading on development of the trachea and lungs, consult Boyden (1972), O'Rahilly and Boyden (1973) and Reid (1976).

**The larynx**

**Comparative anatomy and modification for olfaction and deglutition**

The prime reason for the existence of the larynx is not to make phonation possible, but to provide a protective sphincter at the inlet of the air passages. This can be seen in a lung fish, where the larynx takes the form of a simple muscular sphincter surrounding the opening of the air passage in the floor of the pharynx. In birds, the rima glottidis in the floor
of the mouth shuts to close the air inlet but it makes no sound; phonation occurs from a
dilatation, the syrinx, at the lower end of the trachea just above its bifurcation.

The first breathers of air, the amphibia, do however phonate. They achieve this by
'swallowing' air which, as there is no separate nasal cavity, is drawn in through valvular
'nostrils' opening anteriorly into the roof of the mouth. In mammals, a nasal cavity develops
with the appearance of a palate. The separation of a respiratory and olfactory chamber from
the mouth has considerable advantages: predatory mammals can still breathe while the mouth
is obstructed by prey, and herbivorous prey can still sense warning odours while feeding. In
aquatic vertebrates, such as crocodiles, dolphins and whales, an intranarial larynx has been
developed where the inlet of the larynx is suspended within the nasopharynx and clasped by
the sphincter of the nasopharyngeal inlet (the palatopharyngeus). Thus respiration and
olfaction can continue at the water surface even with the mouth submerged, open and ready
for prey.

The larynx of man is still an essential sphincter, preventing the entry of swallowed
food and other foreign bodies, and providing a blockade to build up pressure for coughing or
for aiding extreme muscular efforts. However, man differs from other mammals in the ability
to produce speech by the highest integrations of the nervous and locomotive systems.

**Descriptive anatomy**

The larynx is situated at the upper end of the trachea; it lies opposite the third to sixth
cervical vertebrae in men, while being somewhat higher in women and children. The average
length, transverse diameter and anteroposterior diameter are, in the male, 44 mm, 43 mm and
36 mm, and, in the female, 36 mm, 41 mm and 26 mm, respectively.

There is little difference in the size of the larynx in boys and girls until after puberty
when the anteroposterior diameter in the male almost doubles.

The skeletal framework of the larynx is formed of cartilages, which are connected by
ligaments and membranes and are moved in relation to one another by both intrinsic and
extrinsic muscles. It is lined with mucous membrane which is continuous above and behind
with that of the pharynx and below with that of the trachea.

The infantile larynx is both absolutely and relatively smaller than the larynx of the
adult. The lumen is therefore disproportionately narrower. It is more funnel-shaped and its
narrowest part is at the junction of the subglottic larynx with the trachea. A very slight
swelling of the lax mucosa in this area may thus produce a very serious obstruction to
breathing. The laryngeal cartilages are much softer in the infant and therefore collapse more
easily in forced inspiratory efforts. The infantile larynx starts high up under the tongue and
with development assumes an increasingly lower position.
Laryngeal cartilages

The thyroid cartilage

This shield-like cartilage is the longest of the laryngeal cartilages and consists of two laminae which meet in the midline inferiorly, leaving the easily palpable thyroid notch between them above. The angle of fusion of the laminae is about 90° in men and 120° in women. In the male, the fused anterior borders form a projection, again easily palpable, which is the laryngeal prominence or 'Adam's apple'. A small narrow strip of cartilage, the intrathyroid cartilage, separates the two laminae anteriorly in childhood. Posteriorly, the laminae diverge and the posterior border of each is prolonged as two slender processes, the superior and inferior cornua. The superior cornu is long and narrow and curves upwards, backwards and medially, ending in a conical extremity to which is attached the lateral thyroid ligament. The inferior cornu is shorter and thicker and curves downwards and medially. On the medial surface of its lower end there is a small oval facet for articulation with the cricoid cartilage.

On the external surface of each lamina, an oblique line curves downwards and forwards from the superior thyroid tubercle, situated just in front of the root of the superior horn, to the inferior thyroid tubercle on the lower border of the lamina. This line marks the attachments of the thyrohyoid, sternothyroid and inferior constrictor muscles. The inner aspects of the laminae are smooth and are mainly covered by loosely attached mucous membrane. The thyroepiglottic ligament is attached to the inner aspect of the thyroid notch, and below this, and on each side of the midline, the vestibular and vocal ligaments, and the thyroarytenoid, thyroepiglottic and vocalis muscles are attached. The fusion of the anterior ends of the two vocal ligaments produces the anterior commissure tendon which is of importance in the spread of carcinoma.

The superior border of each lamina gives attachment to the corresponding half of the thyrohyoid ligament. The inferior border of each half is divided into two by the inferior tubercle. The cricothyroid membrane is attached to the inner aspect of the medial portion of the inferior border of the thyroid cartilage.

The cricoid cartilage

The cricoid cartilage is the only complete cartilaginous ring present in the air passages. It forms the inferior part of the anterior and lateral walls and most of the posterior wall of the larynx. Likened to a signet ring, it comprises a deep broad quadrilateral lamina posteriorly and a narrow arch anteriorly. Near the junction of arch and lamina, an articular facet exists for the inferior cornu of the thyroid cartilage. The lamina has sloping shoulders, which carry articular facets for the arytenoids. These joints are synovial with capsular ligaments. Rotation of the cricoid cartilage on the thyroid cartilage can occur about an axis passing traversely through the joints. A vertical ridge in the midline of the lamina gives attachment to the longitudinal muscle of the oesophagus and produces a shallow concavity on each side for the origin of the posterior cricoarytenoid muscle. The entire surface of the cricoid cartilage is lined with mucous membrane.
The arytenoids and small cartilages

The two arytenoid cartilages are placed close together on the upper and lateral borders of the cricoid lamina. Each is an irregular three-sided pyramid with a forward projection, the vocal process, attached to the vocal folds, and also a lateral projection, the muscular process, which are attached to the posterior cricoarytenoid and lateral cricoarytenoid muscles. Between these two processes is the anterolateral surface which is irregular and divided into two fossae by a crest running from the apex. The upper triangular fossa gives attachment to the vestibular ligament and the lower to the vocalis and lateral cricoarytenoid muscles. The apex is curved backwards and medially and is flattened for articulation with the corniculate cartilage to which is attached the aryepiglottic folds. The medial surfaces are covered with mucous membrane and form the lateral boundary of the intercartilaginous part of the rima glottidis. The posterior surface is covered entirely by the transverse arytenoid muscle.

The base is concave and presents a smooth surface for articulation, with the sloping shoulder on the upper border of the cricoid lamina. The capsular ligament of this synovial joint is lax, allowing both rotary and medial and lateral gliding movements. In man the cylindrical articulating surfaces permit a greater range of gliding than of rotary movement, and the shape of the open human glottis resembles a V. A firm posterior cricoarytenoid ligament prevents forward movement of the arytenoid cartilage.

The corniculate and cuneiform cartilages

The corniculate cartilages are two small conical nodules of elastic fibrocartilage which articulate as a synovial joint, or which are sometimes fused, with the apices of the arytenoid cartilages. They are situated in the posterior parts of the aryepiglottic folds of mucous membrane. The cuneiform cartilages are two small elongated flakes of elastic fibrocartilage placed one in each margin of the aryepiglottic fold.

The cartilage of the epiglottis

The epiglottis is a thin, leaf-like sheet of elastic fibrocartilage which projects upwards behind the tongue and the body of the hyoid bone. The narrow stalk is attached by the thyroepiglottic ligament to the angle between the thyroid laminae, below the thyroid notch. The upper broad part is directed upwards and backwards; its superior margin is free. The sides of the epiglottis are attached to the arytenoid cartilages by the aryepiglottic folds of mucous membrane which, together with the free edge of the epiglottis, form the anterior boundary to the inlet of the larynx. The posterior surface of the epiglottis is concave and smooth but a small central projection, the tubercle, is present in the lower part. The bare cartilage is indented by numbers of small pits into which mucous glands project. The anterior surface of the epiglottis is free and is covered with mucous membrane which is reflected on to the pharyngeal part of the tongue and on to the lateral wall of the pharynx, forming a median glossoepiglottic fold and two lateral glossoepiglottic folds. The depression formed on each side of the median glossoepiglottic fold is the vallecula. An elastic ligament, the hyoepiglottic ligament, connects the lower part of the epiglottis to the hyoid bone in front. The space between the epiglottis and the thyrohyoid membrane is filled with fatty tissue. The epiglottis is not functionally developed in man in that respiration, deglutition and phonation can take place almost normally even if it has been destroyed. In neonates and infants,
however, the epiglottis is omega-shaped. This long, deeply grooved, 'floppy' epiglottis more closely resembles that of aquatic animals and is more suited to its function of protecting the nasotracheal air passage during suckling.

**Calcification of the laryngeal cartilages**

The corniculate and cuneiform cartilages, the epiglottis, and the apices of the arytenoids consist of elastic fibrocartilage, which shows little tendency to calcify. The thyroid, cricoid and greater part of the arytenoids consist of hyaline cartilage which begins to calcify in the person's late teens or early twenties. Calcification of the thyroid cartilage starts in the region of the inferior cornu and proceeds anteriorly and superiorly until the entire rim is involved. A central translucent window persists into old age. Calcification of the posterior part of the lamina of the cricoid and of the posterior part of arytenoid may be confused at radiology with a foreign body (see also under Applied anatomy of larynx). Calcification of the body and muscular process of the arytenoid begins later but the vocal process tends not to ossify.

**The ligaments**

**Extrinsic ligaments**

The extrinsic ligaments connect the cartilages to the hyoid and trachea.

The thyrohyoid membrane stretches between the upper border of the thyroid and the upper border of the posterior surfaces of the body and greater cornua of the hyoid bone. The membrane is composed of fibroelastic tissue and is strengthened anteriorly by condensed fibrous tissue called the median thyrohyoid ligament. The posterior margin is also stretched to form the lateral thyrohyoid ligament which connects the tips of the superior cornua of the thyroid cartilage to the posterior ends of the greater cornua of the hyoid. The ligaments often contain a small nodule, the cartilago triticea. The membrane is pierced by the internal branch of the superior laryngeal nerve and by the superior laryngeal vessels.

The cricotracheal ligament unites the lower border of the cricoid cartilage with the first tracheal ring.

The hyoepiglottic ligament connects the epiglottis to the back of the body of the hyoid.

**Intrinsic ligament**

The intrinsic ligaments connect the cartilages themselves, and together they strengthen the capsules of the intercartilaginous joints and form the broad sheet of fibroelastic tissue, the fibroelastic membrane, which lies beneath the mucous membrane of the larynx and creates an internal framework.

The fibroelastic membrane is divided into an upper and lower part by the laryngeal ventricle. The upper quadrilaterial membrane extends between the border of the epiglottis and the arytenoid cartilage. The upper margin forms the frame of the aryepiglottic fold which is the fibrous skeleton of the laryngeal inlet; the lower margin is thickened to form the
vestibular ligament which underlies the vestibular fold or false cord. The lower part is altogether a thicker membrane, containing many elastic fibres. It is commonly called the cricovocal ligament, cricothyroid ligament or, by a more loose term, the conus elasticus. It is attached below to the upper border of the cricoid cartilage and above is stretched between the midpoint of the laryngeal prominence of the thyroid cartilage anteriorly and the vocal process of the arytenoid behind. The free upper border of this membrane constitutes the vocal ligament, the framework of the vocal fold or true cord. Anteriorly, there is a thickening of the membrane, the cricothyroid ligament, which links the cricoid and the thyroid cartilages in the midline. (For laryngotomy, see under Applied anatomy of the larynx.)

The interior of the larynx

The cavity of the larynx extends from the pharynx at the laryngeal inlet to the beginning of the lumen of the trachea at the lower border of the cricoid cartilage and is divided by the vestibular and vocal folds into three compartments. The superior vestibule is above the vestibular folds, the ventricle or sinus of the larynx lies between the vestibular and vocal folds, and the subglottic space extends from the vocal folds to the lower border of the cricoid cartilage. The fissure between the vestibular folds is called the rima vestibuli and that between the vocal folds is the rima glottidis or glottis. The paraglottic and pre-epiglottic spaces, which are of importance in the spread of tumours, lie within the larynx.

The laryngeal inlet is bounded superiorly by the free edge of the epiglottis and on each side by the aryepiglottic folds. Posteriorly, the inlet is completed by the mucous membrane between the two arytenoid cartilages. There is a plentiful supply of mucous glands in the margins of the aryepiglottic folds.

The superior vestibule lies between the inlet of the larynx and the level of the vestibular folds. It narrows as it extends downwards and the anterior wall, which is the posterior surface of the epiglottis, is much deeper than the posterior wall which is formed by mucous membrane covering the anterior surface of the arytenoid cartilages. There is a plentiful supply of mucous glands in the margins of the aryepiglottic folds.

The middle part of the cavity (and ventricle) lies between the vestibular and vocal folds which cover the ligaments of the same name. On each side, it opens, through a narrow horizontal slit, into an elongated recess, the laryngeal ventricle or sinus. From the anterior part of the ventricle, a pouch, the sacculle of the larynx, ascends between the vestibular folds and the inner surface of the thyroid cartilage. It may extend as far as the upper border of the cartilage; indeed, in some monkeys and apes, it extends even further into the neck, as far as the axilla. In man, the sacculle occasionally protrudes through the thyrohyoid membrane. The mucous membrane lining the sacculle contains numerous mucous glands, lodged in submucous alveolar tissue. Fibrous tissue surrounds the sacculle and a limited number of muscle fibres.
pass from the apex of the arytenoid cartilage across the medial aspect of the saccule to the aryepiglottic fold. The muscle is presumed to compress the saccule and to express the secretion of its mucous glands over the surface of the vocal folds.

The vestibular folds are two thick, pink folds of mucous membrane, each enclosing a narrow band of fibrous tissue, the vestibular ligament, which is fixed in front to the angle of the thyroid cartilage, just below the attachment of the epiglottic cartilage, and behind to the anterolateral surface of the arytenoid cartilage, just above the vocal process.

The vocal folds are two sharp, white folds of mucous membrane closely attached to the vocal ligaments which extend from the middle of the angle of the thyroid cartilage to the vocal processes of the arytenoid cartilages. The vocal ligaments are the free upper margins of the cricovocal membrane and consist of a band of yellow elastic tissue, related on the lateral side to the vocalis muscle; the ligaments are, therefore, capable of stretching and their alteration in shape is fundamental to the production of voice. The vocal folds are covered with stratified squamous epithelium. As a result of the absence of a submucous layer and blood vessels, the vocal fold is a pearly white colour in the living subject.

The rima glottidis or glottis is an elongated fissure between the vocal folds anteriorly, and the vocal processes and bases of the arytenoid cartilages posteriorly. It is limited behind by the mucous membrane between the arytenoid cartilages, at the level of the vocal folds. The region between the vocal folds accounts for three-fifths of the length of the aperture and is termed the 'intermembranous part'. The remainder lies between the vocal processes and is called the intercartilaginous part. The average length of the glottis varies between 23 mm in the male and 16-17 mm in the female. In the resting state, the vocal processes are usually 8 mm apart. The glottis alters shape with phonation and respiration.

The lower part of the laryngeal cavity or subglottic space extends from the level of the vocal folds to the lower border of the cricoid cartilage. Its upper part is elliptical in form, but its lower part widens and becomes circular in shape and continuous with the cavity of the trachea. It is lined with mucous membrane, and its walls consist of the cricothyroid ligament above and the inner surface of the cricoid cartilage below.

The muscles

The muscles of the larynx may be divided into extrinsic, which attach the larynx to neighbouring structures and intrinsic, which move the various cartilages of the larynx.

Extrinsic muscles

The extrinsic muscles are the sternothyroid, thyrohyoid and inferior constrictor of the pharynx. In addition, a few fibres of the stylopharyngeus and palatopharyngeus reach forward to the posterior border of the thyroid cartilage.

The sternothyroid muscle arises from the posterior surface of the manubrium sterni and from the edge of the first, and occasionally the second, costal cartilage, and is inserted into the oblique line on the anterolateral surface of the thyroid lamina. It is supplied by the ansa cervicalis (C2, 3), and depresses the larynx.
The thyrohyoid muscle arises from the oblique line of the thyroid lamina and is inserted into the inferior border of the greater cornu of the hyoid bone. It is supplied by C1 fibres by way of the hypoglossal nerve. This muscle either elevates the larynx if the hyoid is fixed, or depresses the hyoid if the larynx is fixed.

The inferior constrictor muscle is divided into two parts, namely cricopharyngeus and thyropharyngeus, and is described fully in Chapter 10. Although it is attached to the laryngeal cartilages, this muscle has no direct action on laryngeal movement.

The stylopharyngeus muscle arises from the inner surface of the base of the styloid process, passes between the superior and middle constrictors and spreads out beneath the mucous membrane to blend with the inferior constrictors and palatopharyngeus. Some fibres are inserted into the posterior border of the thyroid cartilage. This muscle is supplied by the glossopharyngeal nerve and helps to elevate the larynx.

The palatopharyngeus muscle is described in Chapter 10. It is inserted into the posterior border of the thyroid cartilage and is supplied by the accessory nerve through the pharyngeal plexus. Although its main action is to raise and shorten the wall of the pharynx, this muscle probably helps in the forward tilting of the larynx, thus enabling food to pass straight into the oesophagus during the act of swallowing.

Because the larynx is attached to the hyoid bone by the thyrohyoid membrane, any muscle which elevates the hyoid, such as the mylohyoid, geniohyoid and stylohyoid, will also elevate the larynx, while the sternohyoid and omohyoid will depress it.

The actions of the extrinsic laryngeal muscles can, therefore, be summarized into two categories: elevators of the larynx which include the thyrohyoid (if hyoid is fixed), stylopharyngeus, palatopharyngeus, mylohyoid, geniohyoid and stylohyoid muscles; and depressors of the larynx which include the sternothyroid, sternohyoid and omohyoid muscles.

**Intrinsic muscles**

The intrinsic muscles of the larynx may be divided into: first, those that open and close the glottis, namely the lateral and posterior cricoarytenoids and the transverse and oblique arytenoids; second, those that control the tension of the vocal ligaments, namely the thyroarytenoids, the vocalis and the cricothyroids; and third, those that alter the shape of the inlet of the larynx, namely the aryepiglotticus and the thyroepiglotticus. With the exception of the transverse arytenoid, all these muscles are paired.

The lateral cricoarytenoid arises from the superior border of the lateral part of the arch of the cricoid cartilage and is inserted into the front of the muscular process of the arytenoid. It adducts the vocal ligaments by rotating the arytenoid cartilages medially.

The posterior cricoarytenoid muscle, which is the only muscle to open the glottis, arises from the lower and medial surface of the back of the cricoid lamina and fans out to be inserted into the back of the muscular process of the arytenoid cartilage. Its upper fibres are almost horizontal, while its lateral fibres are almost vertical. The horizontal action rotates the arytenoids and moves the muscular processes towards each other, thus separating the vocal
processes and abducting the vocal ligaments. The vertical action (lateral fibres) draws the arytenoids down the sloping shoulders of the cricoid cartilage, thus separating the arytenoids from each other. These actions occur simultaneously, although in man there is a greater proportion of vertical movement, thus opening the glottis in a V shape. An additional action of the posterior cricoarytenoid muscle is to brace back the arytenoids during phonation, thus preventing the vocal processes from tilting forwards. The weight of the abductor muscles of the larynx is not more than 25% of that of the adductors (Bowden and Sheuer, 1960), which may explain the greater vulnerability of the abductors in the event of partial injury to the recurrent laryngeal nerve. In a study of the intrinsic muscles of 54 normal postmortem larynges, it was observed that while no significant alterations had occurred in the cricothyroid, interarytenoid, lateral cricoarytenoid or thyroarytenoid muscles, all the larynges from patients 13 years old or over revealed microscopical changes in the posterior cricoarytenoid muscle, and in many of those from patients over 46 years old there had also been some necrosis and associated reactive changes to this (Guindi et al, 1981). Because the posterior cricoarytenoid muscle is the sole abductor of the vocal folds, the changes may be a manifestation of the continuous activity of this muscle. The changes start with the deposition of coarse lipofuscin granules near the sarcolemma. Similar granules are found in tongue muscle and in myocardial fibres from an early age. Only in the posterior cricoarytenoid muscle, however, does concomitant muscle and other sarcoplastic change take place.

The interarytenoid muscles comprise the paired oblique arytenoid muscles and the unpaired transverse arytenoid muscle. Each acts as adductor of the vocal folds by approximating the arytenoid cartilages. The transverse arytenoid muscle arises from the posterior surface of the muscular process and the outer edge of one arytenoid and passes to similar attachments on the other cartilage. The oblique arytenoid muscles lie superficial to the transverse arytenoid muscle and pass from the posterior aspect of the muscular process of one arytenoid cartilage to the apex of the other; they, therefore, cross each other. Some of the fibres pass round the apex of the arytenoid cartilage and are prolonged into the aryepiglottic fold as the aryepiglottic muscle which acts as a rather weak sphincter of the laryngeal inlet.

The thyroarytenoid muscles arise from the lower posterior aspect of the junction of the thyroid laminae and from the cricothyroid ligament below. They are inserted into the anterolateral surface of each arytenoid cartilage. Each muscle is in the form of a broad sheet which passes lateral to the vocal ligaments and the cricovocal membrane. The lower part of the muscle is thicker and forms a distinct bundle called the vocalis muscle which is attached posteriorly to the vocal process of the arytenoid and to the lateral surface of the body of the cartilage. It is generally thought that many of the fibres arise from the vocal ligament and do not extend as far forwards as the thyroid cartilage, but this is disputed by some who believe that all its fibres extend from the thyroid cartilage to the arytenoid (Tautz and Rohen, 1967). The muscle is thus more pronounced posteriorly. Contraction of the vocalis pulls up portions of the cricovocal membrane, thereby increasing the vertical depth of the opposing surfaces of the vocal folds. The action of the thyroarytenoid muscles is to draw the arytenoid cartilages towards the thyroid cartilage and thus to shorten the vocal ligaments. At the same time, they rotate the arytenoid cartilages medially and approximate the vocal folds. A considerable number of fibres of the thyroarytenoid are prolonged into the aryepiglottic fold, some continuing to the margin of the epiglottis as the thyroepiglottic muscle which tends to widen the inlet of the larynx by pulling the aryepiglottic folds slightly apart. Occasionally, there is present a very fine muscle, the superior thyroarytenoid, which lies on the lateral surface of
the main mass of the thyroarytenoid and extends obliquely from the angle of the thyroid cartilage to the muscular process of the arytenoid cartilage.

The cricothyroid muscle is the only intrinsic laryngeal muscle which lies outside the cartilaginous framework. It is fan-shaped and arises from the lateral surface of the anterior arch of the cricoid cartilage. Its fibres then diverge and pass backwards in two groups. The lower, oblique fibres pass backwards and laterally to the anterior border of the inferior cornu of the thyroid cartilage, and the upper, straight fibres ascend to the posterior part of the lower border of the thyroid lamina. The cricothyroid muscle rotates the cricoid cartilage about the horizontal axis passing through the cricothyroid joint. The question of whether the thyroid cartilage moves on a fixed cricoid cartilage, as in phonation when the cricoid cartilage is held immovably against the vertebral column by the action of cricopharyngeus, or whether the cricoid cartilage moves on the thyroid cartilage, as in swallowing, it immaterial because the action of the cricothyroid in each case is to lengthen the vocal ligaments by increasing the distance between the angle of the thyroid cartilage and arytenoids.

**Movements of the vocal folds and the anatomy of speech**

The understanding of the movements of the vocal folds during phonation was enhanced by the high-speed film made by the Bell Telephone Laboratories in 1940. This classic film, shot at 4000 frames per second, has been analysed by many observers (Farnsworth, 1940; Pressman, 1942). Other methods of observing vocal fold movements during phonation include frontal tomography (Fink and Kirschner, 1958; Hollien and Curtis, 1960) and stroboscopy (Smith, 1954).

In quiet respiration, the intermembranous part of the glottis is triangular, and the intercartilaginous part is rectangular as the medial surfaces of the arytenoids are parallel.

In forced respiration, the vocal folds undergo extreme abduction; the arytenoid cartilages are rotated laterally and their vocal processes move widely apart. The glottis is thus rhomboid in shape.

Abduction of the vocal folds is effected by the pull of the posterior cricoarytenoid muscles. The arytenoids are laterally rotated and thus the glottis becomes triangular.

Preparatory to phonation, the intermembranous and intercartilaginous parts of the glottis are reduced to a linear chink by the adduction of the vocal folds and adduction and medial rotation of the arytenoid cartilages. The crude adduction is effected by the cricothyroid and lateral cricoarytenoid muscles, and the fine tension of the vocal fold is produced by the tonic contraction of the thyroarytenoid muscle. The interarytenoid muscles, by pulling the arytenoid cartilages together, complete adduction by closing the posterior glottic chink.

The vocal folds are lengthened by the cricothyroid muscles. Because of the nature of the felted membrane of fibroelastic tissue within the vocal folds, squares of this network are converted into diamonds by increasing the length of the vocal folds without a corresponding increase in tension. The tension of the vocal fold is a function of the tonic contraction of the thyroarytenoid muscle which is well designed to produce a wide range of tension in many small steps (Zenker, 1964).
Changes in length and tension control the pitch of the voice and occur normally only when the vocal folds are in contact for phonation.

Three forces act to bring the vocal folds in contact with each other. They are: first, the tension in the fold; second, the decrease in subglottic air pressure which occurs with each vibratory opening of the glottis; and third, the sucking-in effect of escaping air (the Bernoulli effect). The result of this rapidly repeating cycle of opening and closing at the glottis is the release of small puffs from the subglottic air column which form sound waves.

Frontal tomography shows that the area of vocal fold surface in contact with its partners varies according to pitch; at low pitches, the cross-sectional area of the vocal folds is large, but as the pitch raises, the folds become thinner (Hollien and Curtis, 1960).

Stroboscopy demonstrates the presence of both transverse and longitudinal waves in the vocal folds and also the points of contact of the vocal folds.

The function of the vocal folds is to produce sound varying only in intensity and pitch. This is then modified by various resonating chambers above and below the larynx and is ultimately converted into phonemes by the articulating action of the pharynx, tongue, palate, teeth and lips.

Techniques of spectral analysis of the voice show that the vocal tract (larynx, pharynx, mouth and nasal cavities) acts as an intricately selective filter and resonator which propagates a remarkably similar pattern irrespective of the fundamental frequency. This is essential to speech as it ensures that, in spite of a continuously varying tone of voice, a constant quality or timbre is maintained.

Consonants of speech are associated with particular anatomical sites, from which they usually take their designations in the terminology of phonetics; for example, 'p' and 'b' are labials, 't' and 'd' are dentals, and 'm' and 'n' are nasals. These sites have two factors in common. They cause a partial obstruction or constriction at some level in the vocal tract, and they produce an aperiodic vibration or noise which is superimposed on or interrupts the flow of laryngeal tones. For example, dental consonants result from apposition of the top of the tongue to the back of the teeth. This momentarily constricts the passage of escaping air, modifies the resonant parameters of the 'vocal tract' and also generates local noise.

The extreme complexity of speech is reflected in the multiplicity of laryngeal, pharyngeal, hyoid, palatal, lingual and circumoral muscular movements which are combined in rapidly changing combinations to produce phonation and articulation.

**Mucous membranes of the larynx**

The mucous membrane lining the larynx is continuous above with that of the pharynx and below with that of the trachea. It is closely attached over the posterior surface of the epiglottis, over the corniculate and cuneiform cartilages, and over the vocal ligaments. Elsewhere, it is loosely attached and therefore liable to become swollen.
The epithelium of the larynx is either squamous, ciliated columnar or transitional. The upper half of the posterior surface of the epiglottis, the upper part of the aryepiglottic folds and the posterior commissure are covered with squamous epithelium. The vocal folds, which have a fusiform outline, are also covered with squamous epithelium. The height of the vocal fold diminishes towards the anterior commissure mainly because the inferior edge of the vocal fold slopes upwards. The lower edges of the anterior end of the folds form the apex of the triangular fixed part of the subglottis. Thus a tumour reaching or spreading across the anterior commissure might involve the subglottic space (Stell, Gregory and Watt, 1978).

The remainder of the epithelium of the laryngeal mucous membrane is ciliated columnar, except that islands of squamous metaplasia have been found in the subglottic space in 50% of post-mortem larynges taken from non-smokers (Stell, Gregory and Watt, 1980).

Mucous glands are freely distributed throughout the mucous membrane and are particularly numerous on the posterior surface of the epiglottis, where they form indentations into the cartilage, and in the margins of the lower part of the aryepiglottic folds, and in the saccules. The vocal folds do not possess any glands, and the mucous membrane is lubricated by the glands within the saccules. The squamous epithelium covering the vocal folds is therefore vulnerable to desiccation. Scanning electron microscopy has demonstrated the existence not only of microvilli, but also of microridges (microplicae) on the surface cells of the epithelium of the folds and elsewhere in the larynx (Andrews, 1975; Tillmann, Peitsch-Rohrscheider and Hoenges, 1977). Such features have been observed in other epithelia subjected to drying out (for example, the corneal epithelium), and microplicae are regarded as being conducive to the retention of surface secretions.

Some taste buds, similar to those in the tongue, are scattered over the posterior surface of the epiglottis, and in the aryepiglottic folds.

**Blood supply**

The blood supply is derived from the laryngeal branches of the superior and inferior thyroid arteries and the cricothyroid branch of the superior thyroid artery. The superior thyroid artery arises from the external carotid artery, and the inferior thyroid artery arises from the thyrocervical trunk of the first part of the subclavian artery. On the left side, the thoracic duct is an important relation to the commencement of the inferior thyroid artery. It lies in front of either the artery or the thyrocervical trunk, crossing them from medial to lateral side.

The superior laryngeal artery arises from the superior thyroid artery. It passes deep to the thyrohyoid muscle and, together with the internal branch of the superior laryngeal nerve, pierces the thyrohyoid membrane to supply the muscles and mucous membrane of the larynx and to anastomose with branches of its opposite side and with those of the inferior laryngeal artery. The latter arises from the inferior thyroid artery at the level of the lower border of the thyroid gland and ascends on the trachea, together with the recurrent laryngeal nerve. It enters the larynx beneath the lower border of the inferior constrictor muscle and supplies the muscles and mucous membrane. The cricothyroid artery passes from the superior thyroid artery, across the upper part of the cricothyroid ligament and anastomoses with the branch of the opposite side.
The veins leaving the larynx accompany the arteries; the superior vessels enter the internal jugular vein by way of the superior thyroid or facial vein; the inferior vessels drain by way of the inferior thyroid vein into the brachiocephalic veins. Some venous drainage from the larynx is by way of the middle thyroid vein into the internal jugular vein.

**Lymphatic drainage**

The lymphatics of the larynx are separated by the vocal folds into an upper and lower group. The part of the larynx above the vocal folds is drained by vessels which accompany the superior laryngeal vein, pierce the thyrohyoid membrane and empty into the upper deep cervical lymph nodes; whereas the zone below the vocal folds drains, together with the inferior vein, into the lower part of the deep cervical chain often through the prelaryngeal and pretracheal nodes.

The vocal folds are firmly bound down to the underlying vocal ligaments and this results in an absence of lymph vessels, a fact which accounts for the clearly defined watershed between the upper and lower zones.

**Nerve supply**

The nerve supply of the larynx is from the vagus by way of its superior and recurrent laryngeal branches.

The superior laryngeal nerve arises from the inferior ganglion of the vagus and receives a branch from the superior cervical sympathetic ganglion. It descends lateral to the pharynx, behind the internal carotid and, at the level of the greater horn of the hyoid, divides into a small external branch and a larger internal branch. The external branch provides motor supply to the cricothyroid muscle while the internal branch pierces the thyrohyoid membrane above the entrance of the superior laryngeal artery and divides into two main sensory and secretomotor branches. The upper branch supplies the mucous membrane of the lower part of the pharynx, epiglottis, vallecula and vestibule of the larynx. The lower branch descends in the medial wall of the pyriform fossa beneath the mucous membrane and supplies the aryepiglottic fold and the mucous membrane down to the level of the vocal folds.

The internal laryngeal nerve also carries fibres from neuromuscular spindles and other stretch receptors in the larynx. The nerve ends by piercing the inferior constrictor muscle of the pharynx, and unites with an ascending branch of the recurrent laryngeal nerve. This branch is called Galen's anastomosis or loop and is purely sensory.

The recurrent (inferior) laryngeal nerve on the right side leaves the vagus as the latter crosses the right subclavian artery and then loops under the artery and ascends to the larynx in the groove between the oesophagus and trachea. On the left side, the nerve originates from the vagus as it crosses the aortic arch. It then passes under the arch and the ligamentum arteriosum to reach the groove between the oesophagus and trachea. In the neck, both nerves follow the same course and pass upwards accompanied by the laryngeal branch of the inferior thyroid artery, deep to the lower border of the inferior constrictor, and enter the larynx behind the cricothyroid joint. The nerve then divides into motor and sensory branches.
The motor branch has fibres derived from the cranial root of the accessory nerve with cell bodies lying in the nucleus ambiguus; these supply all the intrinsic muscles of the larynx with the exception of the cricothyroid. The sensory branch supplies the laryngeal mucous membrane below the level of the vocal folds and also carries afferent fibres from stretch receptors in the larynx.

As the recurrent laryngeal nerve curves round the subclavian artery or the arch of the aorta, it gives off several cardiac filaments to the deep part of the cardiac plexus. As it ascends in the neck, it gives branches - which are more numerous on the right than the left - the mucous membrane and the muscular coat of the oesophagus and trachea, and some filaments to the inferior constrictor.

**Applied anatomy of the larynx**

**Surface anatomy and laryngotomy**

In the midline from above downwards, it is possible to palpate the hyoid bone, the thyroid cartilage with the laryngeal prominence (Adam's apple), the cricoid cartilage and the trachea. The level of the vocal folds is approximately at the midpoint of the anterior of the thyroid cartilage. By rolling the finger upwards over the cricoid cartilage, it is possible to feel a soft depression between the cricoid and thyroid cartilages. This is the cricothyroid ligament and is the site at which to perform a cricothyrotomy or laryngotomy to relieve upper airway obstruction. This is preferable, as an emergency procedure, to a tracheostomy because of the increased depth of soft tissue associated with an approach to the trachea and the greater likelihood of bleeding from the thyroid isthmus.

**Laryngoscopic examination**

The larynx and surrounding structures can be examined by either indirect or direct laryngoscopy. With a cooperative patient, indirect laryngoscopy, using the laryngeal mirror, will give a good view of the back of the tongue, the valleculae, the epiglottis (which is seen foreshortened), the pyriform fossae and the structures of the larynx. If the patient will not tolerate the laryngeal mirror, there are two options open to the examiner. First, the flexible fibroptic nasolaryngoscope can be passed along the floor of a previously locally anesthetized nasal cavity and then suspended above the larynx to give a direct view. This technique affords an excellent view of the nose and nasopharynx as well as of the larynx and adjacent structures. The laryngeal position is natural in that the patient's tongue is not being pulled out, and the examination is well tolerated by the patient. Second, if a pathological lesion is seen or suspected and a biopsy or removal of tissue is required, then direct laryngoscopy with or without microscopy under general anaesthesia is recommended. This technique will afford a better view of the laryngeal ventricles and of the subglottis.

**Radiology**

A good lateral cervical radiograph will give a wealth of information about the state of the upper airway, signs of obstruction or the presence of foreign bodies. Oedema of the epiglottis or supraglottic structures will be visible, as will stenosis of the subglottis or upper trachea. The normal ventricle is seen as a clear horizontal area. Care must be taken not to
confuse fine lines of calcification in the arytenoid cartilage or the posterior aspect of the thyroid cartilage with foreign bodies. Tomography, computerized tomography (CT) scanning, and contrast laryngography can all aid the diagnosis of laryngeal lesions.

**Injuries to the laryngeal nerves**

There is an intimate and important relationship between the nerves which supply the larynx and the vessels which supply the thyroid gland. In a postoperative study of voice function in 325 patients who had undergone thyroidectomy, Kark et al (1984) found that permanent changes occurred in 35 (25%) after a subtotal thyroidectomy, and in 19 (11%) after lobectomy. The commonest cause of voice change appeared to be injury to the external laryngeal nerves on one or both sides. Damage to the recurrent laryngeal nerve, which was routinely identified and protected, was rarely a cause. They found that when the external laryngeal nerve - which descends over the inferior constrictor muscle immediately deep to the superior thyroid artery and vein as these pass to the superior pole of the gland - was identified and preserved, permanent voice changes occurred in only 5% of cases. This was similar to an incidence of 3% in control patients after endotracheal intubation alone. The functional effect of damage to the external laryngeal nerve is a lower pitched, husky voice that is easily fatigued and has a reduced range. The laryngoscopic changes are much less obvious than those which occur after palsy of the recurrent laryngeal nerve, and their identification may be helped by the use of a stroboscopic light. The edge of the affected vocal fold may be irregular or wavy and usually lies at a lower level, producing an oblique glottic aperture. Recovery after palsy of the external nerve is poor and prognosis is not good (Arnold, 1962).

The recurrent laryngeal nerve comes into close relationship with the inferior thyroid artery as the latter passes medially, behind the common carotid artery, to the gland. The artery may cross posteriorly or anteriorly to the nerve, or the nerve may pass between the terminal branches of the artery. On the right side, there is an equal chance of locating the nerve in each of these three situations; on the left, the nerve is more likely to lie posterior to the artery (Bowden, 1955). Injury to the recurrent nerve is enhanced by its displacement from the normal anatomical locations by the diseased thyroid gland.

Apart from injury occurring at thyroidectomy, the nerve can also be affected by benign or malignant enlargement of the thyroid gland, by enlarged lymph nodes or by cervical trauma. Paralysis of the left nerve, by virtue of its intrathoracic course, is twice as likely to occur as that of the right. It may be involved by malignant tumours of the lung or oesophagus, by malignant or inflamed nodes, by an aneurysm of the aortic arch, or by left atrial hypertrophy associated with mitral stenosis.

The functional effect of damage to one recurrent laryngeal nerve is hoarseness, which later resolves itself almost completely in 50% of patients (Watt-Boolsen et al, 1977), either by a return of function on the affected side or by compensatory over-adduction of the opposite normal vocal fold. Bilateral paralysis, however, results in complete loss of vocal power and a marked inspiratory stridor, usually necessitating tracheostomy. Respiratory obstruction following a thyroidectomy can also result from the collapse of the tracheal cartilages (tracheomalacia) associated with a large goitre or with carcinoma of the thyroid.
External pressure on the trachea from postoperative haemorrhage can also lead to respiratory obstruction.

It is generally accepted that the concept embedded in Semon's law, namely that the abductor nerve or muscle fibres are generally more susceptible to injury, is no longer valid. The 'law', after several amendments, stated: 'In the course of a gradually advancing organic lesion of a recurrent nerve or its fibres in the peripheral trunk of the recurrent nerve, three stages can be observed. In the first stage, only abductor fibres are damaged and the vocal folds approximate in the midline and adduction is still possible. In the second stage, additional contracture of the adductors occurs so that the vocal folds are immobilized in the median position. In the third stage, the adductor becomes paralysed and the vocal fold assumes the cadaveric position'.

Descriptions of multiple positions assumed by paralysed vocal cords still cause confusion.

The hypothesis, attributed to Wagner (1890) and Grossman (1897) - which states, first, that total paralysis of the recurrent nerve immobilizes the vocal fold in the paramedian position because of the adductive action of the intact cricothyroid muscles, and, second, that a 'combined' recurrent laryngeal nerve and superior laryngeal nerve paralysis causes the cord to be immobilized in the intermediate (open or cadaveric) position - is the one preferred by present day laryngologists (Dedo and Dedo, 1980).

This hypothesis is supported by electromyographic and photographic studies of both the human and canine larynx. It is confirmed that the adduction and lengthening effect of an intact cricothyroid muscle is the primary force that holds a paralysed vocal fold in the paramedian position. A vocal fold in the paramedian position is, therefore, paralysed only by a defective recurrent laryngeal nerve, while a vocal fold immobilized in the intermediate position is usually paralysed by a lesion affecting both recurrent and superior laryngeal nerves. The apparent small variations of positions can be attributed to compensation provided by the normal vocal fold crossing the midline, or to atrophy and scarring of the paralysed vocal fold.

Kirchner (1982) stated that if the ipsilateral vagus nerve, as well as the recurrent laryngeal nerve, were injured, the vocal fold might assume the intermediate position because of the loss of the adductor function of the cricothyroid muscle brought about by the interruption of vagal afferent fibres originating in pulmonary stretch receptors. These receptors exert a monitoring effect on the respiratory centre which, in turn, allows reflex adjustments of laryngeal resistance in breathing.

**Trachea and bronchi**

*The trachea*

The trachea is a cartilaginous and membranous tube, about 10-11 cm in length, which extends from its attachment to the lower end of the cricoid cartilage, at the level of the sixth cervical vertebra, to its termination at the bifurcation at the level of the upper border of the fifth thoracic vertebra, or more easily the second costal cartilage or the manubriosternal angle.
The bifurcation moves upwards during the act of swallowing, and downwards and forwards during inspiration, often to the level of the sixth thoracic vertebra. The trachea lies mainly in the median plane, although the bifurcation is usually a little to the right of the midline. The diameter of the air passages increases appreciably during inspiration, and decreases during expiration.

In the child, the trachea is smaller, more deeply placed and more movable than in the adult, and the bifurcation is at a higher level until the age of 10-12 years.

The trachea is D-shaped in cross-section, with incomplete cartilaginous rings anteriorly and laterally, and a straight membranous wall posteriorly. The rings of the trachea can easily be seen endoscopically in outline beneath the mucosa, as they cause a slight elevation and pallor of the mucosa. The transverse diameter is greater than the anteroposterior (about 20 mm compared with 15 mm in the adult male).

Measurements of the internal diameter of the trachea vary from study to study but those given in Table 12.1 (after Engel, 1962) are representative.

The main bronchi and branches

In the adult, the trachea bifurcates into the right and left main bronchi at the level of the second costal cartilage. The main bronchi are separated at their origin by a narrow ridge which, in view of its resemblance to the keel of an upturned boat, is called the carina. The carina always contains cartilage, although the actual dividing ridge is frequently membranous.

Table 12.1 The internal dimensions of the trachea (after Engel, 1962)

<table>
<thead>
<tr>
<th>Age</th>
<th>Average length (cm)</th>
<th>Average diameter (mm)</th>
<th>Sagittal</th>
<th>Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1 months</td>
<td>3.8</td>
<td>5.7</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>1-3 months</td>
<td>4.0</td>
<td>6.5</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>3-6 months</td>
<td>4.2</td>
<td>7.6</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>6-12 months</td>
<td>4.3</td>
<td>7.0</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>1-2 years</td>
<td>4.5</td>
<td>9.4</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>2-3 years</td>
<td>5.0</td>
<td>10.8</td>
<td>9.4</td>
<td></td>
</tr>
<tr>
<td>3-4 years</td>
<td>5.3</td>
<td>9.1</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>6-8 years</td>
<td>5.7</td>
<td>10.4</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>10-12 years</td>
<td>6.3</td>
<td>9.3</td>
<td>12.4</td>
<td></td>
</tr>
<tr>
<td>14-16 years</td>
<td>7.2</td>
<td>13.7</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>9.15</td>
<td>16.5</td>
<td>14.4</td>
<td></td>
</tr>
</tbody>
</table>

The right main bronchus

The definition (to be used in this chapter) of the extent of the right main bronchus is that portion from the tracheal bifurcation to the orifices of the right middle lobe bronchus and the apical segment of the right lower lobe. The right main bronchus is about 5 cm in length. It is wider, shorter and more vertical than the left main bronchus. It has a posterior
membranous wall and a series of cartilage rings which, although smaller in size, are very similar in structure to those of the trachea. The average angle made by the right main bronchus with the trachea is 25-30°. The coronal diameter of the right main bronchus is about 17±4 mm in the male and about 15±4 mm in the female; the corresponding diameter on the left side is 2-3 mm less. The right pulmonary artery is at first below and in front of the right main bronchus and the azygos vein arches over it. The right upper lobe bronchus is given off 2.5 cm along the course of the main bronchus which, on entering the hilum of the lung, divides into a middle and lower lobe bronchus.

The right upper lobe bronchus (1, 2 and 3)

The right upper lobe bronchus arises from the right lateral aspect of the parent bronchus about 12-20 mm from the carina. It runs superolaterally to enter the hilum of the lung. It is about 1 cm in length and divides into three segmental bronchi which supply the apical, posterior and anterior segments of the upper lobe. All these can be seen bronchoscopically with a right-angled telescope or with a fibreoptic bronchoscope. This subdivision is a remarkably constant pattern. The most notable of the few variations that do occur is that of an apical segment supplied by a 'tracheal' bronchus which arises from the right lateral aspect of the trachea just above the carina. Its chief clinical importance is that of the confusion it may cause during the resection of a lung, in the case, for example, of carcinoma.

The apical segmental bronchus (1) passes upwards. After about 1 cm, it divides into apical and anterior subsegmental branches.

The posterior segmental bronchus (2) serves the posterior-inferior part of the superior lobe of the lung and runs backwards and somewhat upwards. It divides into lateral (or axillary) and anterior subsegmental bronchi.

The anterior segmental bronchus (3) runs anteroinferiorly to supply the rest of the superior lobe. After a short distance, it divides into lateral (or axillary) and anterior subsegmental branches.

The right middle lobe bronchus (4 and 5)

The right middle lobe bronchus arises about 2.5 cm beyond the origin of the right upper lobe bronchus from the anterior aspect of the bronchus. It is directed forwards, downwards and laterally, and after a short distance divides into lateral (4) and medial (5) subsegments.

The right lower lobe bronchus (6, 7, 8, 9 and 10)

The right lower lobe bronchus is the continuation of the principal stem beyond the origin of the middle lobe bronchus. It supplies five segments of the lung.

The apical (superior) segmental bronchus (6) arises from the posterior aspect of the termination of the right main bronchus. Its orifice is opposite to and only a short distance
lower than that of the right middle lobe. It subsequently divides into medial, superior and lateral branches, the former two usually arising from a common stem.

In over 50% of right lungs, a subapical (subsuperior) segmental bronchus arises from the posterior surface of the right lower lobe bronchus between 1 and 3 cm below the apical (superior) segmental bronchus. This is distributed to the region of lung between the apical (superior) and posterior basal segments.

The medial basal (cardiac) segmental bronchus (7) has a higher point of origin than the other basal bronchi. It runs inferomedially parallel to the right border of the heart. The lower lobe bronchus then divides into an anterior basal segmental bronchus (8) which descends anteriorly, and a trunk which divides into lateral (9) and posterior (10) basal segments.

The left main bronchus

The left main bronchus is 5.5 cm long and, because it supplies the smaller lung, is narrower than the right main bronchus. In order to reach the hilum of the lung, the main bronchus has to extend laterally beneath the aortic arch. Its angle to the trachea averages 45°. The bronchus crosses anterior to the oesophagus, thoracic duct and descending aorta; the left pulmonary artery lies at first anterior and then superior to it. At the level of the sixth thoracic vertebra, it enters the hilum of the lung and divides into the upper and lower lobe bronchus.

The left upper lobe bronchus (1, 2, 3, 4 and 5)

The left upper lobe bronchus arises from the anterolateral aspect of the parent bronchus about 5.5 cm from the carina. It curves laterally for a short distance and then divides into two bronchi, which correspond to the branches of the right main bronchus to both apical (superior) and middle lobes of the right lung. They are both distributed to the apical (superior) lobe of the left lung, which does not possess a separate middle lobe. The cranial division ascends for about 10 mm before giving off an anterior segmental bronchus (3). It then continues upwards for a further 1 cm as the apicoposterior segmental bronchus (1 and 2), which subsequently subdivides into apical and posterior branches.

The caudal division descends anterolaterally to be distributed to the anteroinferior part of the superior lobe of the left lung. This part of the lung is called the lingular area. The lingular bronchus divides into superior lingular (4) and inferior lingular (5) segmental bronchi.

The left lower lobe bronchus (6, 7, 8, 9 and 10)

The left lower lobe is smaller than the right. The apical (superior) segmental bronchus (6) takes its origin posteriorly from the left lower lobe bronchus about 1 cm below the upper lobe orifice. The inferior lobe bronchus continues for a further 1-2 cm before dividing into two stems, an anteromedial and a posterolateral stem. The medial basal segmental bronchus (7) arises in common with the anterior basal segmental bronchus (8) from the former; the lateral basal segmental bronchus (9) arises in common with the posterior basal segmental bronchus (10) from the latter.
There has not always been recognition of the medial basal segmental bronchus on the left side because of its common origin with the anterior basal segment. However, in 10% of lungs it arises independently from the lower lobe bronchus, and in all cases it supplies a territory similar to its opposite number on the right side.

A subapical (subsuperior) segmental bronchus arises from the posterior surface of the left lower lobe bronchus in as many as 30% of lungs.

**Bronchopulmonary segments**

The lung is divided functionally into a series of bronchopulmonary segments, each with its own bronchus and its own blood supply from the pulmonary artery. Each segment is surrounded by connective tissue, continuous with that of the visceral pleura, and forms a separate respiratory unit of the lung. Modern lung resection surgery, postural drainage and chest radiology are based on the detailed anatomy of these segments (see Applied anatomy of trachea and bronchi).

The segments which have been described in detail previously are summarized in Table 12.2. For further details of bronchopulmonary segmentation, consult Brock (1943, 1954), and Boyd (1955).

**Structure of trachea and major bronchi**

The trachea and extrapulmonary bronchi consist of a framework of incomplete rings of hyaline cartilage, united by fibrous tissue and non-striated muscle. They are lined by mucous membrane.

**The cartilages**

The number of cartilages in the trachea varies from 16 to 20. The cartilages are incomplete rings which stiffen the wall of the trachea both anteriorly and laterally. Behind, where the 'rings' are deficient, the tube is flat and is completed by fibrous and elastic tissue and non-striated muscle fibres. The cartilages measure about 4 mm vertically and 1 mm in thickness. They are placed horizontally one above the other, and are separated by narrow intervals; two or more of the cartilages often unite, partially or completely, and are sometimes bifurcated at their extremities. They are highly elastic, but may become calcified in advanced life. In the extrapulmonary bronchi, the cartilages are shorter, narrower, and rather less regular than those of the trachea, but otherwise they have a similar arrangement.

The first tracheal cartilage is broader than the rest and is sometimes blended with the cricoid cartilages to which it is connected by the cricotracheal ligament. The last tracheal cartilage is thick and broad in the middle where its lower border is prolonged into a triangular process which curves downwards and backwards between the two bronchi forming a bridge called the carina. The C-ring structure persists in the extrapulmonary portion of the bronchial tree where the walls need to be relatively rigid. In the extrapulmonary bronchi, the walls are supported by numerous cartilaginous plates of very varied shape and size. Here the walls need to be relatively mobile and have less tendency to collapse (Vampeperstraete, 1973).
### Table 12.2 The bronchopulmonary segments

<table>
<thead>
<tr>
<th>Right lung</th>
<th>Left lung</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Right upper lobe</strong></td>
<td></td>
</tr>
<tr>
<td>apical segment (1)</td>
<td>apicoposterior segment (1+2)</td>
</tr>
<tr>
<td>posterior segment (2)</td>
<td>anterior segment (3)</td>
</tr>
<tr>
<td>anterior segment (3)</td>
<td>Lingula</td>
</tr>
<tr>
<td><strong>Right middle lobe</strong></td>
<td></td>
</tr>
<tr>
<td>lateral segment (4)</td>
<td>superior segment (4)</td>
</tr>
<tr>
<td>medial segment (5)</td>
<td>inferior segment (5)</td>
</tr>
<tr>
<td><strong>Right lower lobe</strong></td>
<td></td>
</tr>
<tr>
<td>apical segment (6)</td>
<td>apical segment (6)</td>
</tr>
<tr>
<td>medial basal segment (7)</td>
<td>medial basal segment (7)</td>
</tr>
<tr>
<td>anterior basal segment (8)</td>
<td>anterior basal segment (8)</td>
</tr>
<tr>
<td>lateral basal segment (9)</td>
<td>lateral basal segment (9)</td>
</tr>
<tr>
<td>posterior basal segment (10)</td>
<td>posterior basal segment (10)</td>
</tr>
</tbody>
</table>

### The fibrous membrane

Each of the cartilages is enclosed in a perichondrium, which is continuous with a sheet of dense irregular connective tissue forming a fibrous membrane between adjacent 'rings' of cartilage and at the posterior aspect of the trachea and extrapulmonary bronchi where the cartilage is incomplete. The fibrous layer of the perichondrium and the fibrous membrane are composed mainly of collagen intermingled with some elastic fibres. The fibres cross each other diagonally, allowing changes in diameter of the enclosed airway, and the elastic component provides the property of elastic recoil when the membrane is stretched.

Non-striated muscle fibres occur within the fibrous membrane at the back of the tube. Most of these fibres are transverse and are inserted into the perichondrium of the posterior extremities of the cartilages (in the trachea, they are known as the trachealis muscle). Contraction of these fibres, therefore, alters the cross-sectional area of the trachea and bronchi. A few longitudinal muscle fibres lie external to the transverse fibres. The relative thickness of the muscle increases as the branching bronchi become narrower.

### The mucous membrane

The mucous membrane is continuous with, and similar to, that of the larynx above and the intrapulmonary bronchi below. It consists of a layer of pseudostratified ciliated columnar epithelium with numerous goblet cells resting on a broad basement membrane. The cilia beat the overlying layer of mucus upwards to the larynx and pharynx. Deep to the epithelium and its basement membrane are: first, a lamina propria, rich in longitudinal elastic fibres; second, a submucosa of loose irregular connective tissue in which are situated larger blood vessels, nerve trunks and most of the tubular glands and patches of lymphoid tissue; and third, the perichondrium and fibrous membrane, lying deep to the submucosa.
The outer fibrous and muscular layer of the trachea and bronchi is continuous with the fascial planes of surrounding muscles and the oesophagus, and also with the loose areolar tissue of the mediastinum.

The structure of the smaller bronchi

With increased branching of the segmental bronchi, the epithelial lining becomes thinner and, ultimately, single-layered. There are fewer goblet cells, on a narrower basement membrane, in the smaller air passages. The cartilage plates also gradually become smaller and fewer in number, and are not found in the cartilages of smaller bronchi. Circular muscle fibres almost completely surround the tube inside the cartilages, replacing the fibroelastic layer found in the trachea. The muscle fibres contain numerous elastic fibres and are arranged in an interlacing network, partly circular and partly diagonal, so that their contraction constricts and shortens the tube.

The branched tubuloracemose glands are less numerous in the smaller bronchi and are not present in the bronchioles. Lymphoid tissue is found diffused throughout the mucosa of the bronchi, often in solitary nodules and particularly at points of bifurcation.

Blood supply

The blood supply of the trachea is derived mainly from branches of the inferior thyroid arteries. However, the thoracic end is supplied by bronchial arteries which anastomose with the inferior thyroid arteries and also supply the oesophagus in this region. The tracheal veins drain into the thyroid venous plexus.

The bronchi, from the carina to the respiratory bronchioles, lung tissue, visceral pleura and pulmonary nodes are all supplied by the bronchial arteries, which are usually three in number, one for the right lung and two for the left. The left bronchial arteries usually arise from the anterior aspect of the descending thoracic aorta. The right is more variable; it may arise from the aorta, the first intercostal artery, the third intercostal artery (which is the first intercostal branch of the aorta), the internal mammary artery, or the right subclavian artery. The arteries lie against the posterior walls of their respective bronchi.

The bronchial veins form two distinct systems (Marchand, Gilroy and Wilson, 1950). The deep bronchial vein commence as a network in the intrapulmonary bronchioles and communicate freely with the pulmonary veins; they eventually join to form a single trunk which terminates in a main pulmonary vein or in the left atrium. The superficial bronchial veins drain the extrapulmonary bronchi, the visceral pleura and the hilar lymph nodes. They terminate in the azygos vein on the right side, and in the left superior intercostal vein or the accessory (superior) hemiazygos vein on the left side. The bronchial veins do not receive all the blood conveyed to the lungs by the bronchial arteries for the reason that some enters the pulmonary veins.
Lymphatic drainage

The tracheal lymphatics drain to the pretracheal and paratracheal groups of nodes.

The lung has an abundant lymphatic supply which exists as two systems.

The superficial or pleural system form a plexus of lymphatics beneath the pleura and is provided with numerous valves. These lymphatics unite and drain into the hilar lymph nodes. The deep or alveolar system accompanies the pulmonary and bronchial arteries and conveys lymph from the interior of the lung to the hilar nodes. There are few valves, except at points of anastomoses with pleural lymphatics, and at the hilum. The bronchial lymph vessels originate in plexuses beneath the mucous membrane. They then penetrate the muscle coat and form a second plexus in the outer fibrous coat, often incorporating nodules of lymphoid tissue.

The distribution of tracheal and bronchial lymph nodes is shown. These are pulmonary groups of nodes around the smaller bronchi, with bronchopulmonary nodes being mainly beneath the points of division of the intrapulmonary air passages, inferior tracheobronchial nodes being beneath the divisions of the larger bronchi, and a subcoronal group of nodes being beneath the bifurcation of the trachea.

All these nodes subsequently drain to either the right or the left paratracheal nodes by way of the right and left superior tracheobronchial nodes. The right superior tracheobronchial nodes drain the whole of the right lung and also have communications with the left upper lobe. The left superior tracheobronchial nodes drain the greater part of the left lung. The inferior tracheobronchial (subcarinal) group of nodes is important in that these nodes drain lymph from both lungs and, in turn, drain to both right and left paratracheal nodes. Clinically, if these nodes become enlarged, they will cause widening of the carina which will be visible on bronchoscopy. If the nodes are involved in metastatic spread then curative surgery is not feasible.

Lymphatics from the right and left paratracheal nodes unite with vessels from the internal thoracic and brachiocephalic lymph nodes to form the right and left bronchomediastinal trunks which drain either into the right lymphatic duct and left thoracic duct respectively, or independently into the junction of the internal jugular and subclavian veins of their own side.

Nerve supply

The muscle fibres of the trachea, including the trachealis muscle, are innervated by the recurrent laryngeal nerves which also carry sensory fibres from the mucous membrane. Sympathetic nerve fibres are derived mainly from the middle cervical ganglion and have connections with the recurrent laryngeal nerves.

The lungs are supplied from the anterior and posterior pulmonary plexuses situated at the hilum of each lung. The parasympathetic fibres, carried in the vagus nerve, are afferent (cell bodies in the inferior ganglion) and efferent (cell bodies in the dorsal nucleus with relay in the bronchial mucosa). The vagal efferents are bronchoconstrictor to the bronchial muscles,
and secretomotor and vasodilator to the bronchial mucous glands. Afferent fibres are involved in the cough reflex. The efferent sympathetic fibres are postganglionic branches of the second to fifth thoracic ganglion, with an occasional contribution from the first (stellate) ganglion. They are dilator (inhibitory) to the bronchi and pulmonary arterioles. The afferent sympathetic fibres have their cells of origin in the ganglion on the posterior roots of the second to fifth thoracic spinal nerves.

Relations of cervical trachea

Anterior

The central part of the trachea is covered anteriorly by skin, superficial and deep fascia and by the sternohyoid and sternothyroid muscles. The isthmus of the thyroid gland covers a variable number of uppermost rings, usually the second to the fourth. There are thus a large number of layers between skin and trachea that have to be divided, in a tracheostomy operation, in spite of the fact that in a thin subject the trachea is easily palpated in the neck. The trachea in the lower part of the neck is crossed by a communicating band between the anterior jugular veins, as well as by the inferior thyroid veins and, when present, by the thyroidea ima artery which ascends from the arch of the aorta or from the brachiocephalic artery.

Lateral

The right and left lobes of the thyroid gland, which descends to the level of the fifth and sixth tracheal cartilages, lie on either side of the trachea, as does the carotid sheath enclosing the common carotid artery, the internal jugular vein and the vagus nerve. The inferior thyroid artery lies anterolaterally.

Posterior

The oesophagus lies behind the trachea, and in the groove between them is the recurrent laryngeal nerve. Behind the oesophagus are the prevertebral fascia and the vertebral column.

Relations of the thoracic trachea

Anterior

As the trachea descends through the superior mediastinum, it is related anteriorly to the manubrium sterni, the origins of the sternohyoids and sternothyroids and the thymus gland - the latter of which is usually small and insignificant in the adult, but quite large and fleshy in the infant - the inferior thyroid veins, the left brachiocephalic vein, the arch of the aorta, the brachiocephalic and left common carotid arteries, the deep part of the cardiac plexus and a variable number of pretracheal and paratracheal lymph nodes.

It should be noted that in infants the brachiocephalic artery is higher and crosses the trachea just as it descends behind the suprasternal notch. The left brachiocephalic vein may
project upwards into the neck to form an anterior relation of the cervical trachea and a potential hazard during tracheostomy.

**Lateral**

On the left side are the left common carotid and left subclavian arteries, the left vagus nerve and the descending part of the arch of the aorta. The left recurrent laryngeal nerve passes upwards deep to the arch of the aorta and then into the groove between the trachea and oesophagus.

On the right side, the trachea is related to the pleura and upper lobe of the right lung, the right brachiocephalic vein, the superior vena cava, the right vagus nerve and the azygos vein.

**Posterior**

The trachea is related to the oesophagus and, behind it, to the vertebral column. To the left and posterior to the oesophagus lies the thoracic duct.

**Relations of lung root**

The root or hilum of the lung transmits the following structures within a sheath of pleura: the pulmonary artery, the two pulmonary veins, the bronchus, the bronchial vessels, the lymphatics, the lymph nodes and the nerves. The bronchi are situated posterior to the pulmonary vessels. The pulmonary arteries lie above the veins. The bronchial vessels hug the posterior surface of the bronchi. All these structures lie between anterior and posterior pulmonary plexuses. The right side differs from the left in one respect, namely that there is an additional upper lobe bronchus which lies above (‘eparterial’), but still posterior to, the pulmonary vessels.

The following are the relationships of the lung roots themselves.

**Anterior**

On the left is the phrenic nerve, and on the right are the superior vena cava and the phrenic nerve.

**Posterior**

On the left are the descending aorta and vagus nerve, and on the right is the vagus nerve.

**Superior**

On the left is the aortic arch, and on the right the azygos vein.
Inferior

The pulmonary ligaments are merely a sleeve of slack pleura allowing the necessary freedom of 'dead space' for the structures of the lung root.

Applied anatomy of the trachea and bronchi

Surface anatomy of trachea and main bronchi and relationship to tracheostomy

The trachea, which lies about 2 cm under the skin, extends from the cricoid cartilage almost vertically downwards in the median plane as far as the sternal angle, after which it inclines very slightly to the right. The right main bronchus runs from the lower end of the trachea downwards and to the right for 2.5 cm, to reach the hilum of the lung opposite the sternal end of the right third costal cartilage. The left main bronchus runs at a smaller angle from the lower end of the trachea for 5 cm to the left and downwards to reach the hilum of the lung behind the left third costal cartilage, 3.5 cm from the median plane.

In order to increase the proportion of cervical trachea before a tracheostomy, the head is extended maximally by placing a sandbag between the shoulders. The cricoid cartilage is palpated and the skin incision in the adult is placed approximately 2.5 cm below this level. From the cosmetic point of view, a short collar skin incision is preferable to a vertical one. By staying exactly in the midline, danger to the major vessels in the neck is avoided. The pretracheal muscles are separated and the thyroid isthmus is either displaced upwards or downwards or divided. The trachea is opened between the second and third rings. In the adult, a window is cut out of the front of the trachea by removing a part of the second and third, or the third and fourth rings. In the child, the cartilages are very soft and a vertical incision is sufficient to introduce a tube. Care must always be taken not to damage the first tracheal ring. As mentioned previously, the left brachiocephalic vein may project up into the neck in children, and the close relationship of the brachiocephalic artery to the trachea has led to a sudden profuse haemorrhage in consequence of the tracheal wall's being eroded by a tracheostomy tube.

Examination of trachea and bronchi by tracheoscopy and bronchoscopy, and clinical significance of bronchopulmonary segments

Tracheoscopy and bronchoscopy

Tracheoscopy and bronchoscopy can be performed under local or general anaesthesia using either rigid or fibreoptic instruments. At the present time, the most common method is probably that of fibreoptic instrumentation under local anaesthesia combined with controlled sedation. Examination of the trachea and bronchi enables pathological states to be studied and biopsies for histology to be taken, foreign bodies to be removed, or accumulation of fluid to be removed by suction.

Bronchoscopy is an exercise in the practical knowledge of the bronchopulmonary segments.
The trachea is a glistening tube which has a white appearance where there are rings of cartilage and a reddish appearance in the areas between them. The tube appears slightly flattened where it is crossed by the aortic arch, and pulsations are visible. The tracheal bifurcation or carina lies slightly to the left of the midtracheal line because of the more vertically placed right main bronchus. It is consequently easier to advance initially down this bronchus. With the aid of the retrograde telescope or, alternatively, by bending the tip of the fibrescope, the orifices of the anterior, posterior and apical branches of the right upper lobe can be seen. Further advance will reveal a horizontal ridge marking the anteriorly placed orifice of the middle lobe bronchus, below which the lower lobe bronchus lies. Posteriorly, the latter's apical branch orifice can be seen; then the medial (cardiac) orifice appears and, finally, placed close together, from above downwards, appear the anterior, lateral and posterior basal orifices. If the instrument is now withdrawn into the trachea and advanced along the left main bronchus, the first impression is that of the greater length of the bronchus before the appearance of the left upper lobe in the lateral wall. The mouth of the lingula bronchus can best be seen through a retrograde telescope or by bending the tip of the fibrescope. The advance along the lower lobe bronchus brings the apical and medial basal branches into view posteriorly and then, beyond this, the cluster of orifices of the anterior, lateral and posterior basal bronchi.

Clinical significance of bronchopulmonary segments

The right main bronchus is more nearly in line with the trachea than is the left. It is easier, therefore, for inhaled foreign bodies or fluids, such as gastric contents, to enter the right rather than the left bronchial tree. If the patient is lying on his side, such material enters the lateral (or 'axillary') subsegments of the anterior and posterior segments of the lobe. They are thus a frequent site for the development of inhalational pneumonitis, segmental collapse or of a lung abscess.

If the patient is supine then the apical (superior) segmental bronchus, which arises from the posterior aspect of the right or left lower lobe bronchi, is the most likely part of the lung for aspirated material to collect. It was formerly, also, a not uncommon site for a tubercular cavity.

When inhaled, foreign bodies may, according to their size, obstruct either a main, lobe, segmental or smaller bronchus.

While pathological conditions, such as bronchiectasis, and certain infective processes may be restricted to one or more bronchopulmonary segments, malignant neoplasms and tuberculosis break through from one segment to adjacent ones.

If appropriate, surgical resection of a single bronchopulmonary segment can be undertaken. More radical procedures include the removal of a number of segments, of a whole pulmonary lobe (lobectomy), or of a complete lung (pneumonectomy).