

Part 1

The Respiratory Pathway, Lungs, Thoracic Wall and Diaphragm

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The mouth

The mouth is made up of the vestibule and the mouth cavity, the former communicating with the latter through the aperture of the mouth.

The *vestibule* is formed by the lips and cheeks without, and by the gums and teeth within. An important feature is the opening of the *parotid duct* on a small papilla opposite the 2nd upper molar tooth. Normally the walls of the vestibule are kept together by the tone of the facial muscles; a characteristic feature of a facial (VII) nerve paralysis is that the cheek falls away from the teeth and gums, enabling food and drink to collect in, and dribble out of, the now patulous vestibule.

The *mouth cavity* (Fig. 1) is bounded by the alveolar arch of the maxilla and the mandible, and teeth in front, the hard and soft palate above, the anterior two-thirds of the tongue and the reflection of its mucosa forwards onto the mandible below, and the oropharyngeal isthmus behind.

The mucosa of the floor of the mouth between the tongue and mandible bears the median *frenulum linguae*, on either side of which are the orifices of the submandibular salivary glands (Fig. 2). Backwards and outwards from these ducts extend the sublingual folds that cover the sublingual glands on each side (Fig. 3); the majority of the ducts of these glands open as a series of tiny orifices along the overlying fold, but some drain into the duct of the submandibular gland (Wharton's duct).

Inspect your mouth in a mirror. Elevate your tongue, then press on one or the other side onto your submandibular gland beneath the angle of the jaw. You will see a jet of saliva emerge from the orifice of the submandibular duct at the tip of the sublingual fold. While about it, pull your cheek laterally with a finger, press on your parotid gland on that side and observe a jet of saliva emerge from the parotid duct, which lies at the level of your 2nd upper molar tooth.

The palate

The *hard palate* is made up of the palatine processes of the maxillae and the horizontal plates of the palatine bones. The mucous membrane covering the hard palate is peculiar in that the stratified squamous mucosa is closely connected to the underlying periosteum, so that the two dissect away at operation as a single sheet termed the mucoperiosteum. This is thin in the midline, but thicker more laterally owing to the presence of numerous small palatine salivary glands, an uncommon but well-recognized site for the development of mixed salivary tumours.

The *soft palate* hangs like a curtain suspended from the posterior edge of the hard palate. Its free border bears the *uvula* centrally and blends on either side with the pharyngeal wall. The anterior aspect of this curtain faces the mouth cavity and is covered by a stratified squamous epithelium. The posterior aspect is part of the nasopharynx and is lined by a ciliated columnar epithelium under which is a thick stratum of mucous and serous glands embedded in lymphoid tissue.

4 The respiratory pathway, lungs, thoracic wall and diaphragm

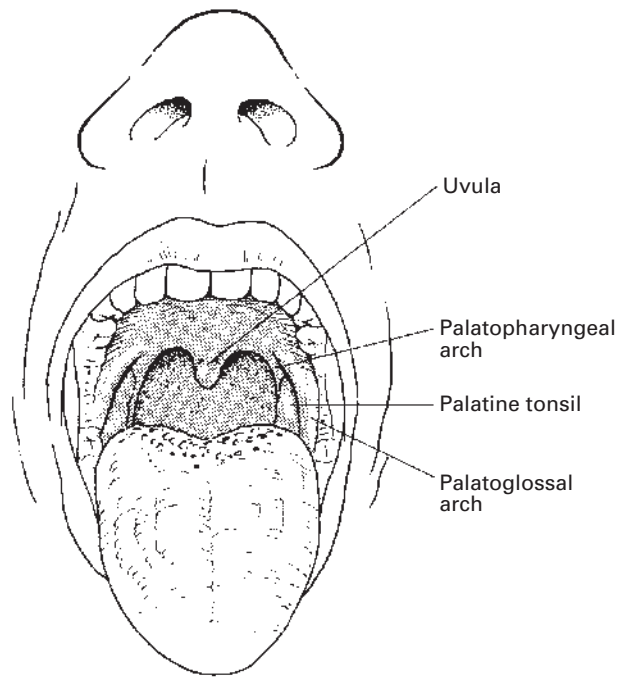


Fig. 1 View of the open mouth with the tongue depressed.

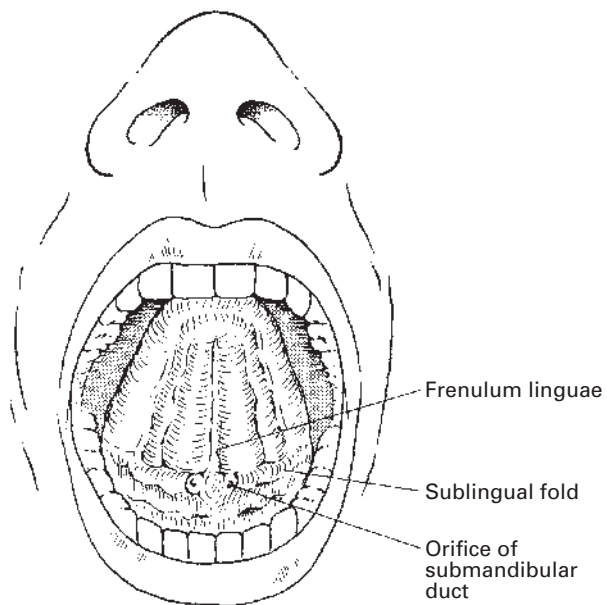
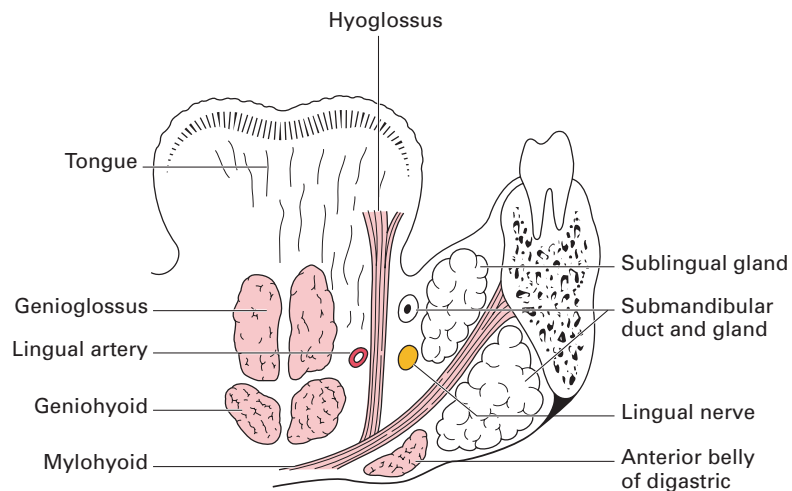


Fig. 2 View of the open mouth with the tongue elevated.

Fig. 3 Coronal section through the floor of the mouth.



The 'skeleton' of the soft palate is a tough fibrous sheet termed the *palatine aponeurosis*, which is attached to the posterior edge of the hard palate. The aponeurosis is continuous on each side with the tendon of tensor palati and may, in fact, represent an expansion of this tendon.

The *muscles of the soft palate* are five in number: the tensor palati, the levator palati, the palatoglossus, the palatopharyngeus and the musculus uvulae (see Fig. 13).

The *tensor palati* arises from the scaphoid fossa at the root of the medial pterygoid plate, from the lateral side of the Eustachian cartilage and the medial side of the spine of the sphenoid. Its fibres descend laterally to the superior constrictor and the medial pterygoid plate to end in a tendon that pierces the pharynx then loops medially around the hook of the hamulus to be inserted into the palatine aponeurosis. Its action is to tighten and flatten the soft palate.

The *levator palati* arises from the undersurface of the petrous temporal bone and from the medial side of the Eustachian tube, enters the upper surface of the soft palate and meets its fellow of the opposite side. It elevates the soft palate.

The *palatoglossus* arises in the soft palate, descends in the palatoglossal fold and blends with the side of the tongue. It approximates the palatoglossal folds.

The *palatopharyngeus* descends from the soft palate in the palatopharyngeal fold to merge into the side wall of the pharynx: some fibres become inserted along the posterior border of the thyroid cartilage. It approximates the palatopharyngeal folds.

The *musculus uvulae* takes origin from the palatine aponeurosis at the posterior nasal spine of the palatine bone and is inserted into the uvula. Injury to the cranial root of the accessory nerve, which supplies this muscle via the vagus nerve, results in the uvula becoming drawn across and upwards towards the opposite side.

6 The respiratory pathway, lungs, thoracic wall and diaphragm

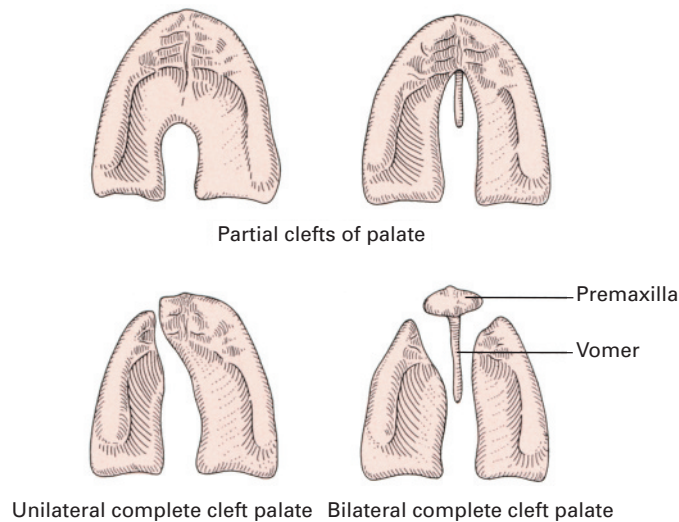


Fig. 4 Types of cleft palate deformity.

The tensor palati is innervated by the mandibular branch of the trigeminal nerve via the otic ganglion (see page 274). The other palatine muscles are supplied by the pharyngeal plexus of the vagus nerve, which transmits cranial fibres of the accessory nerve via the vagus.

The palatine muscles help to close off the nasopharynx from the mouth in deglutition and phonation. In this, they are aided by contraction of the upper part of the superior constrictor, which produces a transverse ridge on the back and side walls of the pharynx at the level of the 2nd cervical vertebra termed the *ridge of Passavant*.

Paralysis of the palatine muscles results (just as surely as a severe degree of cleft palate deformity) in a typical nasal speech and in regurgitation of food through the nose.

Cleft palate

The palate develops from a central premaxilla and a pair of lateral maxillary processes: the former usually bears all four (occasionally only two) of the incisor teeth. All degrees of failure of fusion of these three processes may take place. There may be a complete cleft, which passes to one or both sides of the premaxilla; in the latter case, the premaxilla prolapses forwards to produce a marked deformity. Partial clefts of the posterior palate may involve the uvula only (bifid uvula), involve the soft palate or encroach into the posterior part of the hard palate (Fig. 4).

The nose

The nose is divided anatomically into the external nose and the nasal cavity.

The nose 7

The *external nose* is formed by an upper framework of bone (made up of the nasal bones, the nasal part of the frontal bones and the frontal processes of the maxillae), a series of cartilages in the lower part, and a small zone of fibrofatty tissue that forms the lateral margin of the nostril (the ala). The cartilage of the nasal septum constitutes the central support of this framework.

The *cavity of the nose* is subdivided by the nasal septum into two quite separate compartments that open to the exterior by the *nares* and into the nasopharynx by the posterior nasal apertures or *choanae*. Immediately within the nares is a small dilatation, the *vestibule*, which is lined in its lower part by stiff straight hairs.

Each side of the nose presents a roof, a floor and a medial and lateral wall.

The *roof* first slopes upwards and backwards to form the bridge of the nose (the nasal and frontal bones), then has a horizontal part (the cribriform plate of the ethmoid), and finally a downward-sloping segment (the body of the sphenoid).

The *floor* is concave from side to side and slightly so from before backwards. It is formed by the palatine process of the maxilla and the horizontal plate of the palatine bone.

The *medial wall* (Fig. 5) is the nasal septum, formed by the septal cartilage, the perpendicular plate of the ethmoid and the vomer. Deviations of the septum are very common; in fact, they are present to some degree in about 75% of the adult population. Probably nearly all are traumatic in

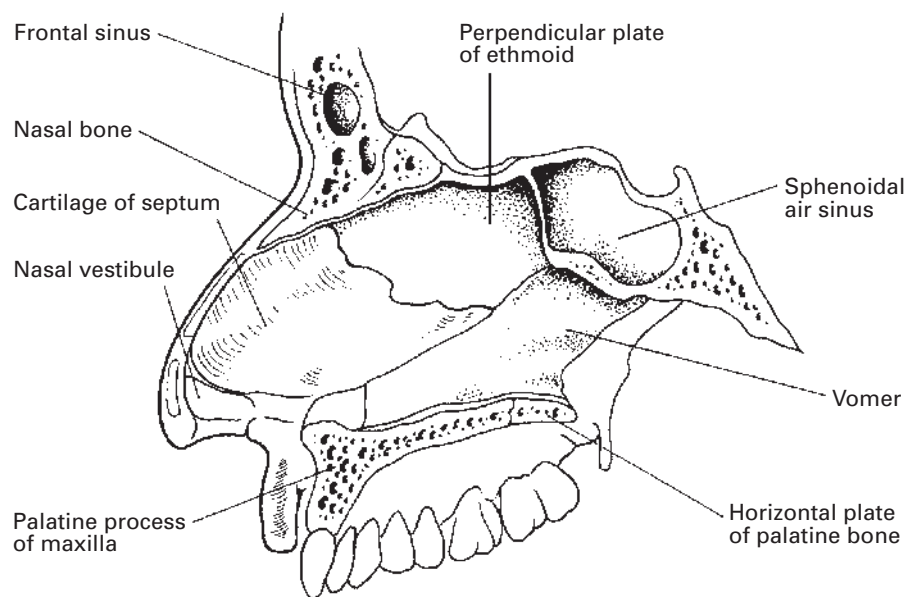


Fig. 5 The septum of the nose.

8 The respiratory pathway, lungs, thoracic wall and diaphragm

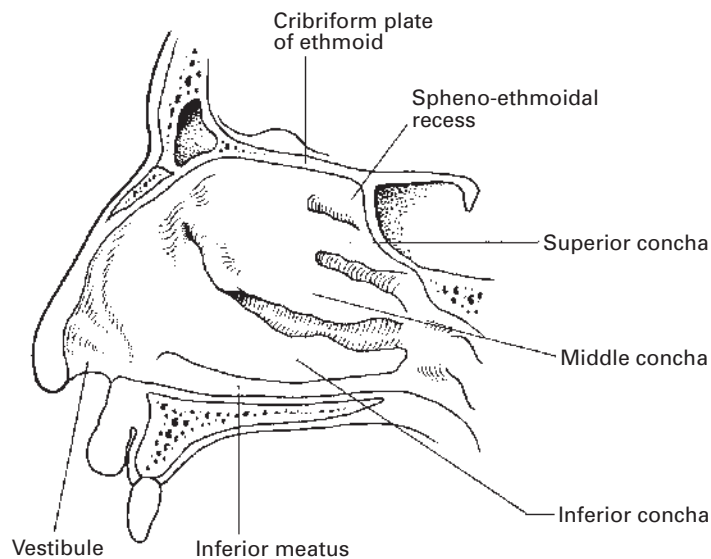


Fig. 6 The lateral wall of the right nasal cavity.

origin, and result from quite minor injuries in childhood or even at birth. The deformity does not usually manifest itself until the second dentition appears, when rapid growth in the region produces deflections from what had been an unrecognized minor dislocation of the septal cartilage. Males are more commonly affected than females, a distribution which would favour this traumatic theory. Both nostrils may become blocked, either from a sigmoid deformity of the cartilage or from compensatory hypertrophy of the conchae on the opposite side. The deviation is nearly always confined to the anterior part of the septum.

The *lateral wall* (Fig. 6) has a bony framework made up principally of the nasal aspect of the ethmoidal labyrinth above, the nasal surface of the maxilla below and in front, and the perpendicular plate of the palatine bone behind. This is supplemented by the three scroll-like conchae (or turbinate bones), each arching over a *meatus*. The upper and middle *conchae* are derived from the medial aspect of the ethmoid labyrinth; the inferior concha is a separate bone.

Onto the lateral wall open the orifices of the paranasal sinuses (see page 9) and the nasolacrimal duct; the arrangement of these orifices is shown in Fig. 7.

The sphenoid sinus opens into the *spheno-ethmoidal recess*, a depression between the short superior concha and the anterior surface of the body of the sphenoid. The posterior ethmoidal cells drain into the superior meatus. The middle ethmoidal cells bulge into the middle meatus to form an elevation, termed the *bulva ethmoidalis*, onto which they open. Below the bulva is a cleft, the *hiatus semilunaris*, into which opens the ostium of the maxillary sinus. The hiatus semilunaris curves forwards in front of the bulva ethmoidalis as a passage termed the *infundibulum*, which drains the anterior ethmoidal air cells. In about 50% of cases the frontal sinus drains into the

The nose 9

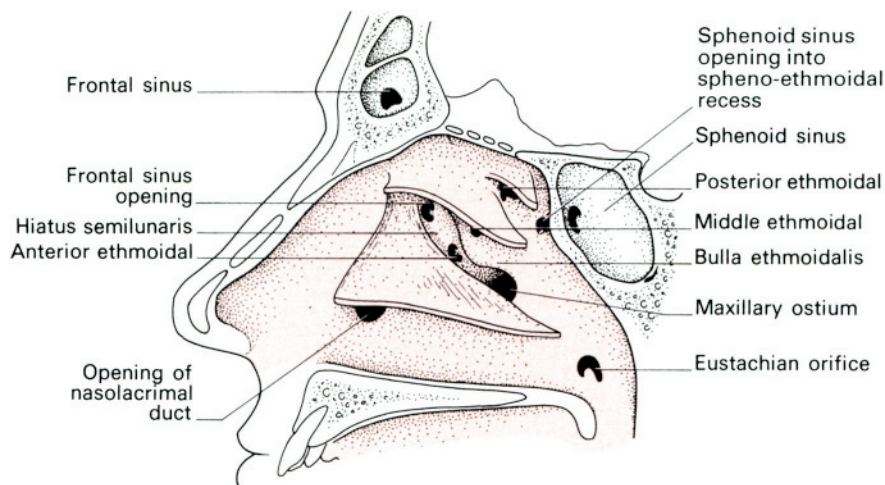


Fig. 7 The lateral wall of the right nasal cavity; the conchae have been partially removed.

infundibulum via the frontonasal duct. In the remainder, this duct opens into the anterior extremity of the middle meatus.

The nasolacrimal duct drains tears into the anterior end of the inferior meatus in solitary splendour.

The paranasal sinuses

The paranasal air sinuses comprise the maxillary, sphenoid, frontal and ethmoidal sinuses. They are, in effect, the outpouchings from the lateral wall of the nasal cavity into which they drain; they all differ considerably from subject to subject in their size and extent, and they are rarely symmetrical. There are traces of the maxillary and sphenoid sinuses in the newborn; the rest become evident about the age of 7 or 8 years in association with the eruption of the second dentition and lengthening of the face. They only become fully developed at adolescence.

The *maxillary sinus* (the antrum of Highmore) is the largest of the sinuses. It is pyramid-shaped, and occupies the body of the maxilla (Fig. 8). The base of this pyramid is the lateral wall of the nasal cavity and its apex points laterally towards the zygomatic process.

The floor of the sinus extends into the alveolar process of the maxilla, which lies approximately 1.25 cm below the level of the floor of the nose. Bulges in the floor are produced by the roots of at least the 1st and 2nd molars; the number of such projections is variable and may include all the teeth derived from the maxillary process, i.e. the canine, premolars and molars. The floor may actually be perforated by one or more of the roots.

The roof is formed by the orbital plate of the maxilla, which bears the canal of the infra-orbital branch of the maxillary nerve. Medially, the antrum drains into the middle meatus; the ostium is situated high up on

10 The respiratory pathway, lungs, thoracic wall and diaphragm

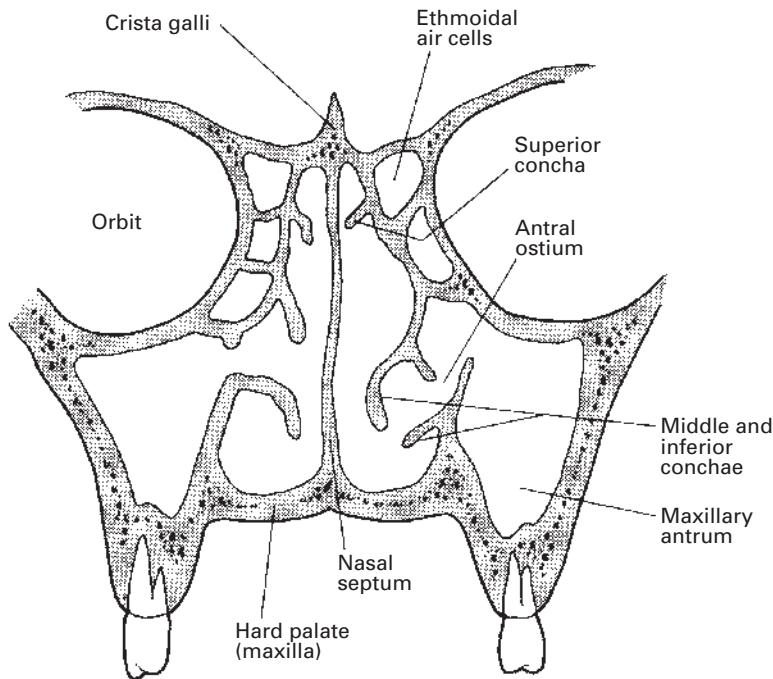


Fig. 8 The maxillary sinus in coronal section.

this wall and is thus inefficiently placed from the mechanical point of view. Drainage from this sinus is therefore dependent on the effectiveness of the cilia lining its wall. There may be one or more accessory openings from the antrum into the middle meatus.

The *sphenoid sinuses* lie side by side in the body of the sphenoid. Occasionally, they extend into the basisphenoid and the clinoid processes. They are seldom equal in size, and the septum between them is usually incomplete. They open into the sphenoid-ethmoidal recess.

The *frontal sinuses* occupy the frontal bone above the orbits and the root of the nose. They are usually unequal, and their dividing septum may be incomplete. It is interesting that their extent is in no way related to the size of the superciliary ridges. They drain through the frontonasal duct into the middle meatus.

The *ethmoidal sinuses* or air cells are made up of some 8–10 loculi suspended from the outer extremity of the cribriform plate of the ethmoid and bounded laterally by its orbital plate. They thus occupy the upper lateral wall of the nasal cavity. The cells are divided into anterior, middle and posterior groups by bony septa; their openings have already been described above.

Blood supply

The upper part of the nasal cavity receives its arterial supply from the anterior and posterior ethmoidal branches of the ophthalmic artery, a branch

of the internal carotid artery. The sphenopalatine branch of the maxillary artery is distributed to the lower part of the cavity and links up with the septal branch of the superior labial branch of the facial artery on the antero-inferior part of the septum. It is from this zone, just within the vestibule of the nose, that epistaxis occurs in some 90% of cases (Little's area).

A rich submucous venous plexus drains into the sphenopalatine, facial and ophthalmic veins, and through the last links up with the cavernous sinus. Small tributaries also pass through the cribriform plate to veins on the undersurface of the orbital lobe of the brain. These connections account for the potential danger of boils and other infections within and adjacent to the nose.

Nerve supply

The olfactory nerve (I) supplies the specialized olfactory zone of the nose, which occupies an area of some 2 cm² in the uppermost parts of the septum and lateral walls of the nasal cavity (see page 247).

The nerves of common sensation are derived from the nasociliary branch of the 1st division of the trigeminal nerve (V') and also from the 2nd, or maxillary, division (V''). These nerves are considered fully in Chapter 6, but may conveniently be summarized here.

- 1 The *septum* (Fig. 9) is supplied, in the main, by the nasopalatine nerve, derived from V'' via the pterygopalatine ganglion. The posterosuperior corner receives branches of the medial posterosuperior nasal nerves from the same source, and the anterior part of the septum is supplied

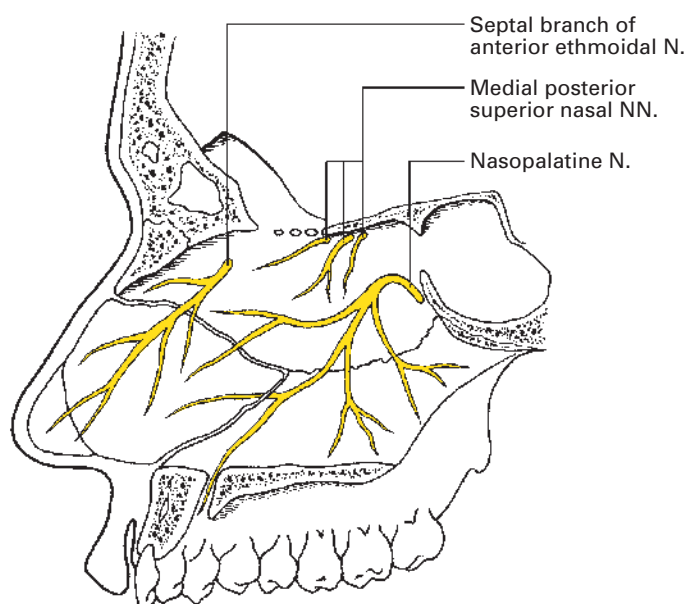


Fig. 9 The nerve supply of the nasal septum.

12 The respiratory pathway, lungs, thoracic wall and diaphragm

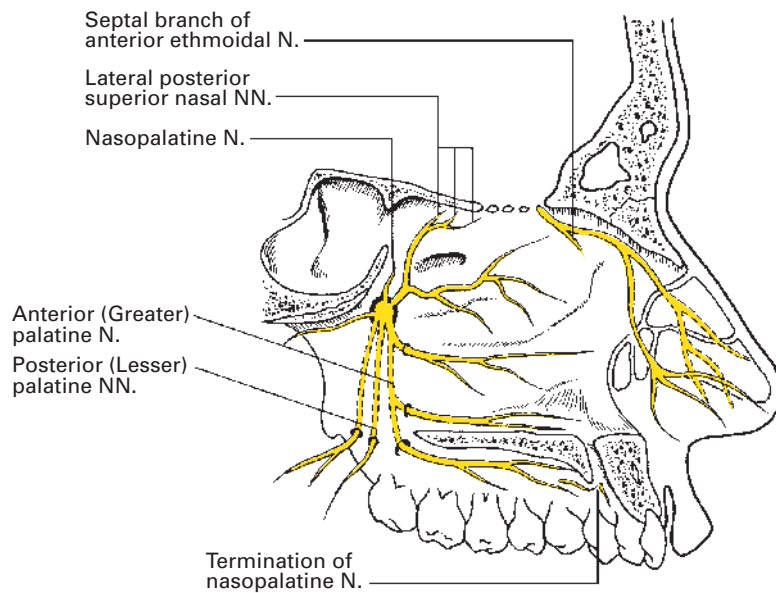


Fig. 10 The nerve supply of the lateral wall of the nose.

- by the septal branches of the anterior ethmoidal nerve (a branch of the nasociliary branch of V').
- 2 The *lateral wall* (Fig. 10) is innervated in its upper part, in the region of the superior and middle conchae, by the lateral posterior superior nasal nerve. The inferior concha receives branches from the anterior superior alveolar nerve (arising from the maxillary nerve in the infra-orbital canal) and from the anterior (greater) palatine nerve (derived from the pterygopalatine ganglion). The anterior part of the lateral wall, in front of the conchae, is supplied by the anterior ethmoidal branch of the nasociliary nerve. This branch then leaves the nasal cavity between the nasal bone and the upper nasal cartilage to become the external nasal nerve, which supplies the outer aspect of the nose; the anterior ethmoidal nerve thus innervates the cartilaginous tip of the nose on both its inner and outer aspects.
 - 3 The *floor* is supplied in its anterior part by the anterosuperior alveolar nerve and posteriorly by the anterior (greater) palatine nerve.
 - 4 The *vestibule* receives terminal twigs of the infra-orbital branch of the maxillary nerve, which also supplies the skin immediately lateral to, and beneath, the nose.
 - 5 The *paranasal sinuses* are innervated by V' and V''. The maxillary sinus is supplied entirely by the maxillary nerve; its roof by the infra-orbital nerve, floor by the anterior palatine nerve, medial wall by the medial posterosuperior nasal and the anterior (greater) palatine nerves, and the anterior, posterior and lateral walls by the superior alveolar branches. The other sinuses are supplied by the ophthalmic division of V: the ethmoidal and sphenoidal sinuses by the anterior and posterior ethmoidal

nerves, and the frontal sinus by the supra-orbital and supratrochlear nerves.

Structure

The vestibule is lined by a stratified squamous epithelium bearing stiff straight hairs, sebaceous glands and sweat glands. The remainder of the nasal cavity, apart from the small olfactory area, bears tall columnar ciliated cells interspersed with mucus-secreting goblet cells, and forms a continuous epithelial sheet with the mucosa of the nasal sinuses. Beneath the epithelium is a highly vascular connective tissue containing copious lymphoid aggregates and carrying mucous and serous glands. The mucous membrane is thick and velvety over the greater part of the nasal septum and over the conchae. However, it is thin over the septum immediately within the vestibule (where the blood vessels of Little's area show through the mucosa) and also over the meati and the floor of the nose.

The mucosa of the nose, and its accessory sinuses, is closely adherent to the underlying periosteum or perichondrium; surgically, the two layers strip away together and, as in the hard palate, are termed the mucoperiosteum.

The functions of the nose

The nose acts as a respiratory pathway, through which air becomes warmed, humidified and filtered, as the organ of olfaction and as a resonator in speech.

There is a strong inborn reflex to breathe through the nose. This is natural to the survival of babies during suckling. As a result, nasal obstruction may cause gross discomfort; thus, packing the nose after surgery may cause restlessness upon emergence from an anaesthetic, and choanal atresia may cause cyanosis in the newborn. The natural expiratory resistance of the upper airways is of the order of 1–2 cmH₂O and can be increased subconsciously to provide a natural form of continuous positive airway pressure. Intubation of the trachea decreases this natural expiratory resistance.

Air passes through the nose, not directly along the inferior meatus, but in a curve through the upper reaches of the nasal cavity. The vascular cavernous plexuses, arranged longitudinally like so many radiator pipes, increase the temperature of the air to that of the body by the time it reaches the nasopharynx. Water, derived partly from the mucous and serous glands, partly from the goblet cells, but mainly by exudation from the mucous surfaces, produces nearly 100% saturation of the inhaled air. Filtration is effected by the blanket of mucus covering the nasal cavity and its related sinuses. The mucus is swept towards the pharynx like a sticky conveyor belt by the action of the cilia and then swallowed. Reflex sneezing also helps rid the nose of irritants.

The blood supply to the nasal mucosa is under reflex control. General warming of the subject produces reflex hyperaemia whereas general

14 The respiratory pathway, lungs, thoracic wall and diaphragm

cooling results in vasoconstriction. Hence the well-known observation that one's stuffy nose in a hot room clears on going out into the cold air.

A part of the Horner's syndrome produced in a cervical sympathetic block (see page 162) is blockage of the nasal passage on that side as a result of paralysis of sympathetic vasoconstrictor fibres to the nasal mucosa.

CLINICAL NOTE

Nasal intubation

The major nasal air passage lies beneath the inferior concha, and a nasotracheal tube should be encouraged to use this passage by passing it directly backwards along the floor of the nose. Occasionally, the posterior end of the inferior turbinate may be hypertrophied and may offer resistance to the easy passage of the tube. The delicate mucosa of the nose and the posterior pharyngeal wall may easily be torn, and force must never be used in this manoeuvre. Cases are on record of nasal tubes being passed through the mucosa of the posterior pharyngeal wall into the retropharyngeal space and of serious haemorrhage from injury to the posterior ethmoidal vessels, which are branches of the internal carotid artery via the ophthalmic artery and therefore impossible to control by proximal ligation. It can be seen from Fig. 11 that a nasotracheal tube must curve anteriorly as it passes through the nasopharynx. It may be possible to pass a well-curved tube in a 'blind' manner, but more flexible tubes will need assistance if they are to be passed through the vocal cords. Magill's intubating forceps are commonly used for

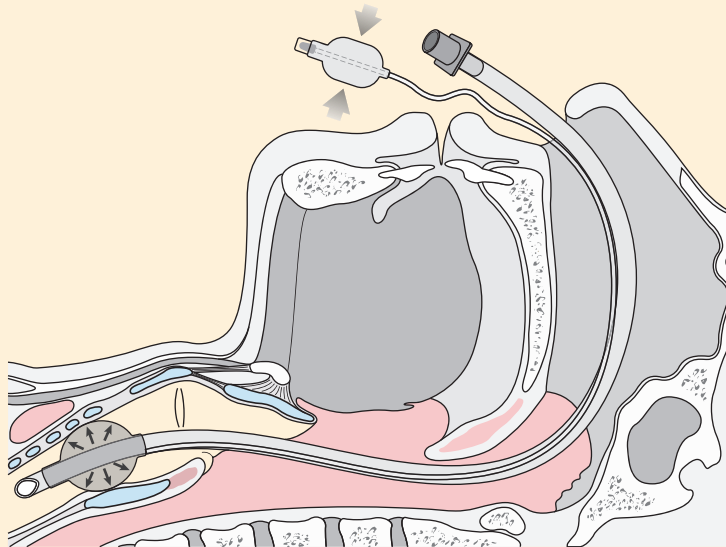


Fig. 11 Nasal intubation; note the curvatures of the tracheal tube.

this purpose. A well-curved and rigid tube may increase the chances of success of attempts at blind nasal intubation, but may also increase the chances of trauma to the anterior tracheal wall. Experienced operators often manipulate the larynx with one hand and intubate with the other. Confirmation of intubation may be visual by laryngoscopy or by capnography (measurement of exhaled CO₂).

The pharynx

The pharynx is a wide muscular tube that forms the common upper pathway of the respiratory and alimentary tracts. Anteriorly, it is in free communication with the nasal cavity, the mouth and the larynx, which conveniently divide it into three parts, termed the nasopharynx, oropharynx and laryngopharynx, respectively (Figs 12, 13). In extent, it reaches from the skull (the basilar part of the occipital bone) to the origin of the oesophagus at the level of the 6th cervical vertebra (C6). Posteriorly, it rests against the cervical vertebrae and the prevertebral fascia.

The nasopharynx

The nasopharynx lies behind the nasal cavity and above the soft palate. It communicates with the oropharynx through the pharyngeal isthmus, which becomes closed off during the act of swallowing (see page 21). On the lateral wall of the nasopharynx, 1 cm behind and just below the

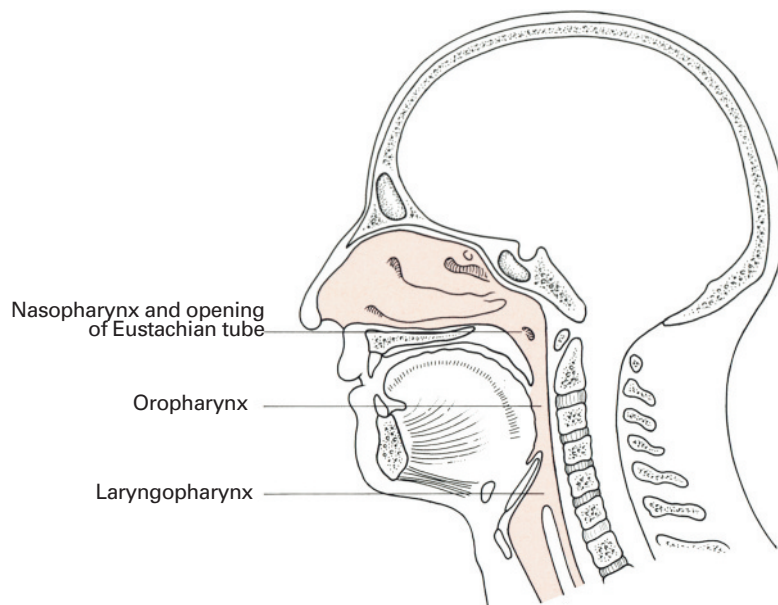


Fig. 12 A sagittal section through the head and neck to show the subdivisions of the pharynx.

16 The respiratory pathway, lungs, thoracic wall and diaphragm

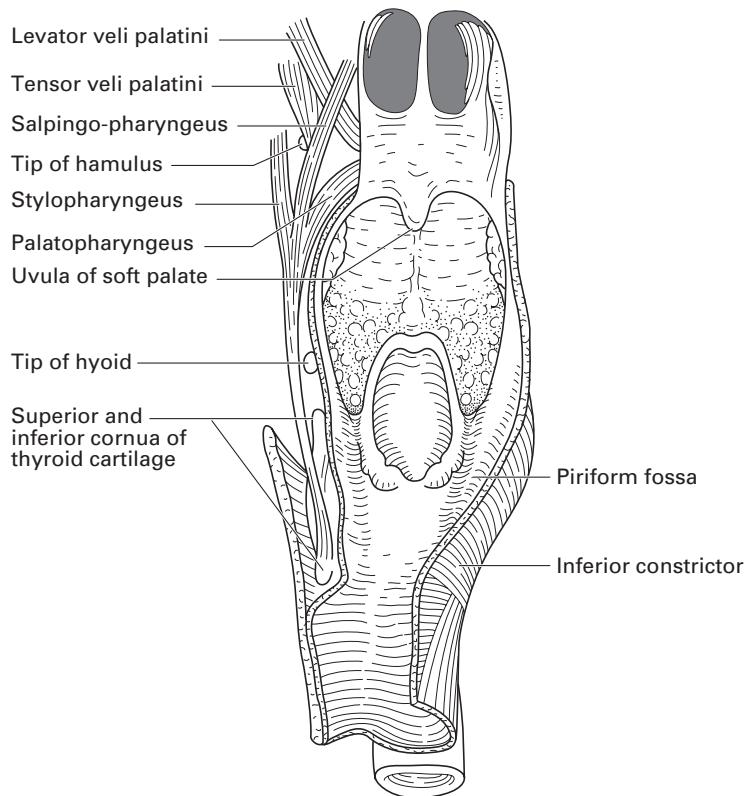


Fig. 13 The pharynx: the posterior wall has been removed and the interior is viewed from behind. On the left side the palatal muscles have been exposed.

inferior nasal concha, lies the pharyngeal opening of the *pharyngotympanic* (*Eustachian*) tube. The underlying cartilage of the tube produces a bulge immediately behind its opening, termed the *tubal elevation*, and behind this, in turn, is a small depression, the *pharyngeal recess* – fossa of Rosenmüller (Fig. 7).

The *nasopharyngeal tonsil* ('adenoids') lies on the roof and posterior wall of the nasopharynx. It consists of a collection of lymphoid tissue covered by ciliated epithelium and lies directly against the superior constrictor muscle; it has no well-defined fibrous capsule. The lymphoid tissue begins to atrophy at puberty and has all but disappeared by early adult life.

Posterosuperiorly to the nasopharynx lies the sphenoid sinus that separates the pharynx from the sella turcica containing the pituitary gland. This is the basis of the transnasal approach to the pituitary.

The oropharynx

The mouth cavity leads into the oropharynx through the oropharyngeal isthmus, which is bounded by the palatoglossal arches, the soft palate and the dorsum of the tongue (Fig. 1). The oropharynx itself extends in height

The pharynx 17

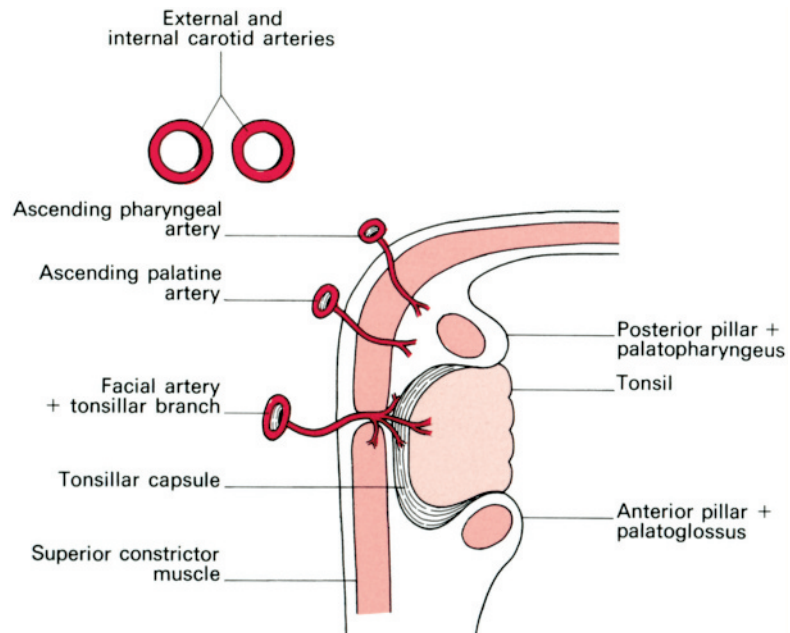


Fig. 14 Diagram of the tonsil and its surroundings in horizontal section.

from the soft palate to the tip of the epiglottis. Its most important features are the tonsils.

The *palatine tonsils* are the collections of lymphoid tissue that lie on each side in the triangle formed by the palatoglossal and palatopharyngeal arches (the pillars of the fauces), connected across the base by the dorsum of the tongue (Fig. 1). The free surface of each palatine tonsil presents about 12–20 tonsillar pits, and its upper part bears the intratonsillar cleft. This free surface is covered by a stratified squamous epithelium: the unique combination of squamous epithelium with underlying lymphoid tissue renders a section through the tonsil unmistakable under the microscope.

The deep surface of the palatine tonsil may send processes of lymphoid tissue into the dorsum of the tongue, into the soft palate and into the faucal pillars. The palatine tonsil is bounded on this deep aspect by a dense fibrous *capsule* of thickened pharyngeal aponeurosis, which is separated by a film of lax connective tissue from the underlying superior constrictor muscle (Fig. 14). In the absence of inflammation, this capsule enables complete enucleation of the tonsil to be effected. However, after repeated quinsies, the capsule becomes adherent to the underlying muscle and tonsillectomy then requires sharp dissection.

Vascular, lymphatic and nerve supply

The principal blood supply of the palatine tonsil is the tonsillar branch of the facial artery which, accompanied by its two venae comitantes, pierces the superior constrictor muscle to enter the inferior pole of the tonsil. In

18 The respiratory pathway, lungs, thoracic wall and diaphragm

In addition, twigs from the lingual, ascending palatine, ascending pharyngeal and maxillary arteries all add their contributions. Venous drainage passes into the venae comitantes of the tonsillar branch of the facial artery and also into a paratonsillar vein that descends from the soft palate across the outer aspect of the tonsillar capsule to pierce the pharyngeal wall into the pharyngeal venous plexus. It is this vein which is the cause of occasional unpleasant venous bleeding after tonsillectomy. The internal carotid artery, it should be noted, is a precious 2.5 cm away from the tonsillar capsule, and is out of harm's way during tonsillectomy (Fig. 14).

Lymph drainage is to the upper deep cervical nodes, particularly to the jugulo-digastric node (or tonsillar node) at the point where the common facial vein joins the internal jugular vein.

There is a threefold sensory nerve supply:

- 1 the glossopharyngeal nerve via the pharyngeal plexus;
- 2 the posterior palatine branch of the maxillary nerve;
- 3 twigs from the lingual branch of the mandibular nerve.

For this reason, infiltration anaesthesia of the tonsil is more practicable than attempts at nerve blockade.

The palatine and pharyngeal tonsils, together with lymph collections on the posterior part of the tongue and in relation to the Eustachian orifice, form a more or less continuous ring of lymphoid tissue around the pharyngeal entrance, which is termed Waldeyer's ring.

The laryngopharynx

The third part of the pharynx extends from the tip of the epiglottis to the lower border of the cricoid at the level of C6 (Fig. 13). Its anterior aspect faces first the laryngeal inlet, bounded by the aryepiglottic folds, then, below this, the posterior aspects of the arytenoids, and finally the cricoid cartilage. The larynx bulges back into the centre of the laryngopharynx, leaving a recess on either side termed the *piriform fossa*. It is here that swallowed sharp foreign bodies such as fish bones tend to impact.

The internal branch of the superior laryngeal nerve passes in the submucosa of the piriform fossa. Local anaesthetic solutions applied to the surface of the piriform fossa on wool balls held in Krause's forceps will produce anaesthesia of the larynx above the vocal cords. This is a useful nerve block to supplement oral anaesthesia for laryngoscopy.

The structure of the pharynx

The pharynx has four coats: mucous, fibrous, muscular and fascial:

- 1 The mucosa is stratified squamous except in the nasopharynx, which is lined by a ciliated columnar epithelium. Beneath the surface are numerous mucous racemose glands.
- 2 The fibrous layer is relatively dense above (the *pharyngobasilar fascia*), where the muscle wall is deficient; it is also condensed to form the capsule of the tonsil and the posterior median raphe, but elsewhere it is thin.

- 3 The muscular coat is described below.
- 4 The fascial coat is the buccopharyngeal fascia, which is the very thin fibrous capsule of the pharynx.

CLINICAL NOTE

Ludwig's angina

Because of the fascial coat, inflammatory oedema may spread downwards from infections within the mouth or the tonsils or from dental sepsis. The spread of the oedema is restricted by the pharyngeal fascia and produces swelling and oedema of the tissues of the larynx and pharynx. This may produce difficulty in swallowing and then rapidly progresses to laryngeal obstruction unless the seriousness of the situation is realized and surgical drainage of the deep pharyngeal tissues performed. Similar complications can occur after operations involving the floor of the mouth. The anaesthetist should always consider the advisability of tracheostomy in these patients.

The muscles of the pharynx

The muscles of the pharynx are the superior, middle and inferior constrictors (which have been aptly likened to three flower-pots fitted into each other), the stylopharyngeus, salpingopharyngeus and palatopharyngeus.

The constrictor muscles (Fig. 15) have an extensive origin from the skull, mandible, hyoid and larynx on either side; they sweep round the pharynx to become inserted into the median raphe, which runs the length of the posterior aspect of the pharynx, being attached above to the pharyngeal

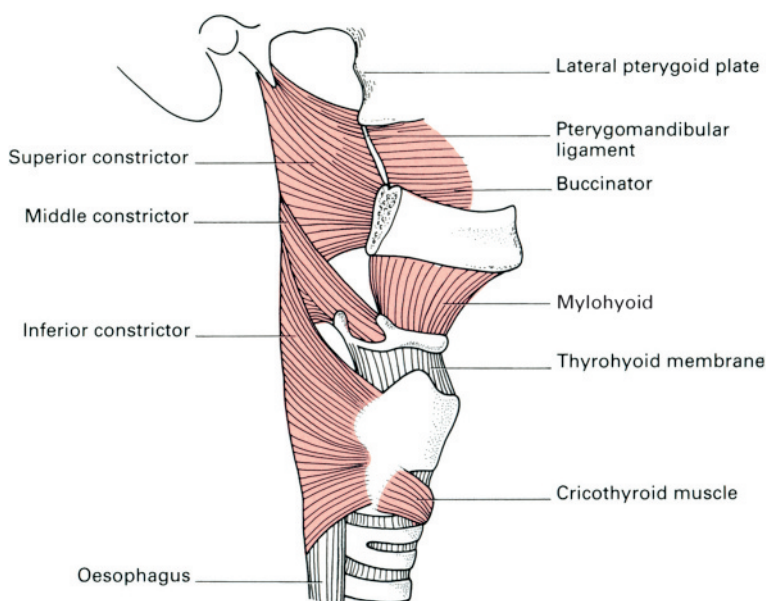


Fig. 15 The constrictor muscles of the pharynx.

20 The respiratory pathway, lungs, thoracic wall and diaphragm

tubercle on the basilar part of the occipital bone and blending below with the oesophageal wall.

The *superior constrictor* muscle arises from the lower part of the medial pterygoid plate, the pterygoid hamulus, the pterygomandibular raphe and the posterior end of the mylohyoid line on the inner aspect of the mandible. The space between its upper free margin and the base of the skull allows the Eustachian tube to pass into the nasopharynx.

The *middle constrictor* spreads out like a fan from the lesser horn of the hyoid, the upper border of the greater horn and the lowermost part of the stylohyoid ligament.

The *inferior constrictor*, which is the thickest of the three, arises from the side of the cricoid, from the tendinous arch over the cricothyroid muscle and from the oblique line on the lamina of the thyroid cartilage. The muscle consists functionally of two parts: the lower portion, arising from the cricoid (the cricopharyngeus), acts as a sphincter, and its fibres are arranged transversely; the upper portion, with obliquely placed fibres that arise from the thyroid cartilage, has a propulsive action. Inco-ordination between these two components, so that the cricopharyngeus is in spasm while the thyropharyngeal element is initiating powerful peristalsis, is thought to be the aetiological basis for the development of a pharyngeal pouch. This first develops at a point of weakness posteriorly in the midline at the junction between the two portions of the muscle (Killian's dehiscence). As the pouch enlarges, it impinges first against the vertebral column, and then becomes deflected, usually to the more exposed left side (Fig. 16).

The constrictor muscles are supplied by the pharyngeal nerve plexus, which transmits the fibres of the accessory nerve in the pharyngeal branch of the vagus. In addition, the inferior constrictor receives filaments from the external branch of the superior laryngeal and the recurrent laryngeal branch of the vagus.

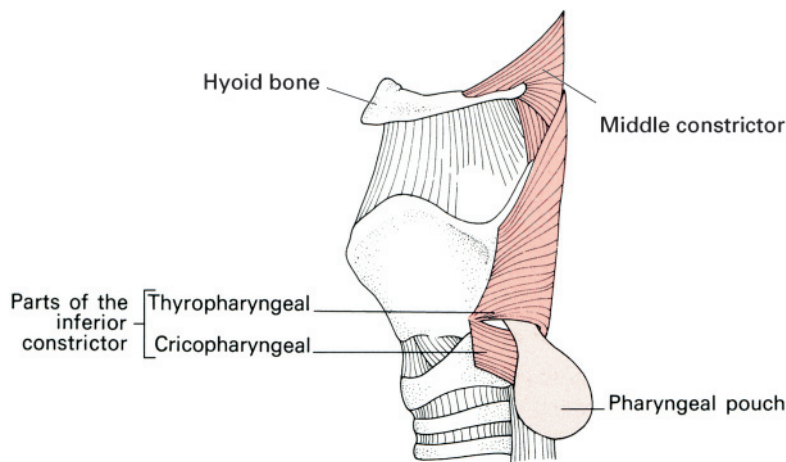


Fig. 16 The pharyngeal pouch emerging between the two components of the inferior constrictor muscle.

Deglutition

The act of swallowing not only conveys food down the oesophagus but also disposes of mucus loaded with dust and bacteria from the respiratory passages. Moreover, during deglutition, the Eustachian auditory tube is opened, thus equalizing the pressure on either side of the ear drum.

Deglutition is a complex, orderly series of reflexes. It is initiated voluntarily but is completed by involuntary reflex actions set up by stimulation of the pharynx; if the pharynx is anaesthetized, normal swallowing cannot take place. The reflexes are co-ordinated by the deglutition centre in the medulla, which lies near the vagal nucleus and the respiratory centres.

The food is first crushed by mastication and lubricated by saliva; it is a common experience that it is well-nigh impossible to swallow a pill when the throat is dry. The bolus is then pushed back through the oropharyngeal isthmus by the pressure of the tongue against the palate, assisted by the muscles of the mouth floor.

During swallowing, the oral, nasal and laryngeal openings must be closed off to prevent regurgitation through them of food or fluid: each of these openings is guarded by a highly effective sphincter mechanism.

The nasopharynx is closed by elevation of the soft palate, which shuts against a contracted ridge of superior pharyngeal constrictor, the ridge of Passavant. At the same time, the tensor palati opens the ostium of the Eustachian tube. The oropharyngeal isthmus is blocked by contraction of palatoglossus on each side, which narrows the space between the anterior faucal pillars: the residual gap is closed by the dorsum of the tongue wedging into it.

The protection of the larynx is a complex affair, brought about not only by closure of the sphincter mechanism of the larynx but also by tucking the larynx behind the overhanging mass of the tongue and by utilizing the epiglottis to guide the bolus away from the laryngeal entrance. This mechanism may be interfered with as a result of an anterior flap tracheostomy (Bjork's tracheostomy). The consequent fixation of the trachea may limit mobility of the larynx and prevent its elevation during swallowing, resulting in aspiration of fluid into the trachea. The normal protective reflex is lost after the application of local anaesthetic solutions to the pharynx and after surgical interference with the pharyngeal muscles. The central nervous component of the swallowing reflex is depressed by opioids, anaesthesia and cerebral trauma. In these circumstances, aspiration of foreign material into the pulmonary tree becomes possible, particularly if the patient is lying on his/her back or in a head-up position.

The laryngeal sphincters are at three levels:

- 1 The aryepiglottic folds, defining the laryngeal inlet, which are apposed by the aryepiglottic and oblique interarytenoid muscles.
- 2 The walls of the vestibule of the larynx, which are approximated by the thyro-epiglottic muscles.
- 3 The vocal cords, which are closed by the lateral cricoarytenoid and transverse interarytenoid muscles.

22 The respiratory pathway, lungs, thoracic wall and diaphragm

The larynx is elevated and pulled forwards by the action of the thyrohyoid, stylohyoid, stylopharyngeus, digastric and mylohyoid muscles so that it comes into apposition with the base of the tongue, which is projecting backwards at this phase. While the larynx is raised and its entrance closed, there is reflex inhibition of respiration.

As the head of a bolus of food reaches the epiglottis, it is first tipped backwards against the pharyngeal wall and momentarily holds up the onward passage of the food. The larynx is then elevated and pulled forwards, drawing with it the epiglottis so that it now stands erect, guiding the food bolus into streams along both piriform fossae and away from the laryngeal orifice, like a rock that juts into a waterfall that will deviate the stream to either side. A little spill of fluid occurs into the laryngeal vestibule, often reaching as far as the false cords but seldom passing beyond them. Finally, the epiglottis flaps backwards as a cover over the laryngeal inlet, but this occurs only after the main bolus has passed beyond it. The epiglottis appears to act as a laryngeal lid at this stage to prevent deposition of fragments of food debris over the inlet of the larynx during re-establishment of the airway.

The cricopharyngeus then relaxes, allowing the bolus to cross the pharyngo-oesophageal junction. Fluids may shoot down the oesophagus passively under the initial impetus of the tongue action; semi-solid or solid material is carried down by peristalsis. The oesophageal transit time is about 15 seconds, relaxation of the cardia occurring just before the peristaltic wave reaches it. Gravity has little effect on the transit of the bolus, which occurs just as rapidly in the lying as in the erect position. It is, of course, quite easy to swallow fluid or solids while standing on one's head, a well-known party trick; here oesophageal transit is inevitably an active muscular process.

CLINICAL NOTE

The airway during anaesthesia

It is commonly perceived that, when a patient is anaesthetized in the supine position, the airway readily becomes obstructed as a result of the muscles of the jaw becoming relaxed and the tongue falling back to obstruct the oropharynx (Fig. 17a,b). This obstruction can be decreased by the use of an oropharyngeal airway. Studies have revealed that this may not be the complete explanation. Radiographs taken during induction of anaesthesia have shown that a more important cause of this obstruction is the blockage of the nasopharyngeal air passage brought about by the soft palate falling back onto the posterior nasopharyngeal mucosa. The sequence of events appears to be as follows:

- 1 the tongue obstructs the oral airway by impinging on the palate (hence snoring);
 - 2 the nasal airway is blocked by the falling back of the soft palate.
- Relief of either of these obstructions will produce a clear airway.

The introduction of the laryngeal mask airway, inserted through the mouth to the laryngeal aperture, in which a cuff is inflated to produce a seal over the laryngeal orifice (Fig. 18), has provided an effective method of overcoming airway obstruction in the pharynx. Its use obviates the need to pull the tongue forwards manually in order to relieve the posterior pharyngeal obstruction in general anaesthesia.

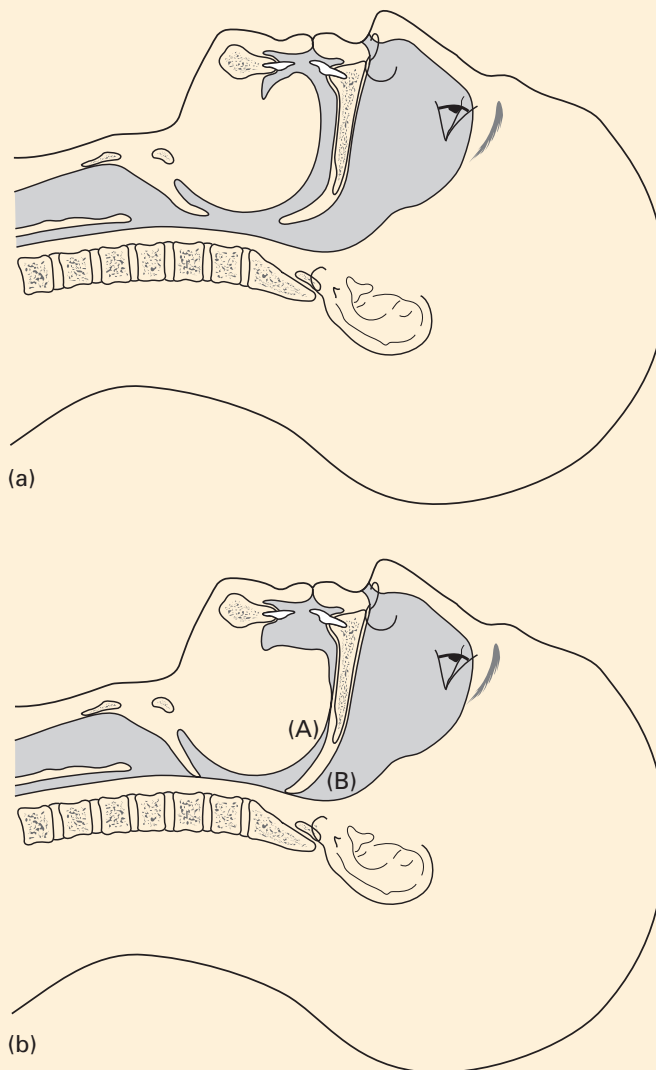


Fig. 17 (a) The relationship of the tongue to the posterior wall of the pharynx in the supine position in the conscious patient. (b) After induction of anaesthesia; both the tongue (A) and soft palate (B) move posteriorly.

24 The respiratory pathway, lungs, thoracic wall and diaphragm

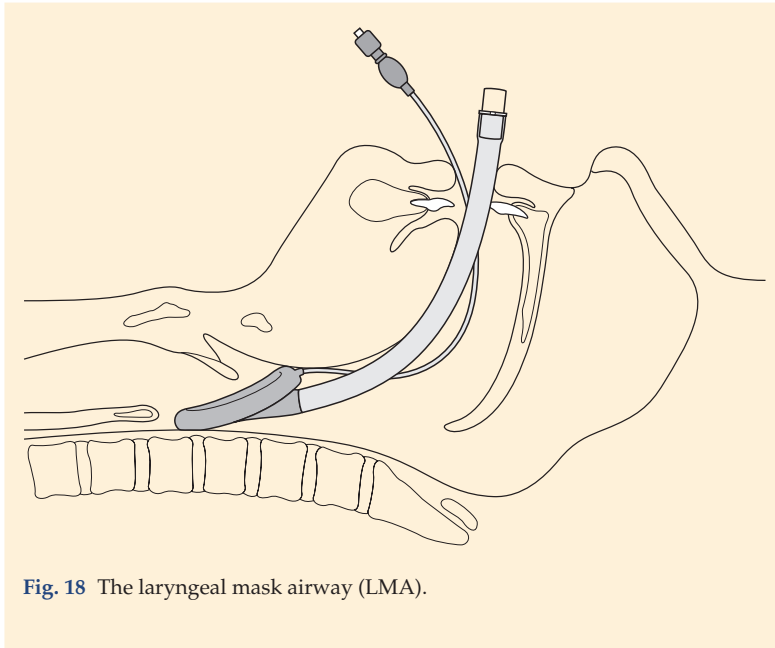


Fig. 18 The laryngeal mask airway (LMA).

The larynx

The competent anaesthetist should have a level of knowledge of the anatomy of the larynx of which a laryngologist would not be ashamed.

Evolutionally, the larynx is essentially a protective valve at the upper end of the respiratory passages to protect against inhalation of food during swallowing; its development into an organ of speech is a much later affair.

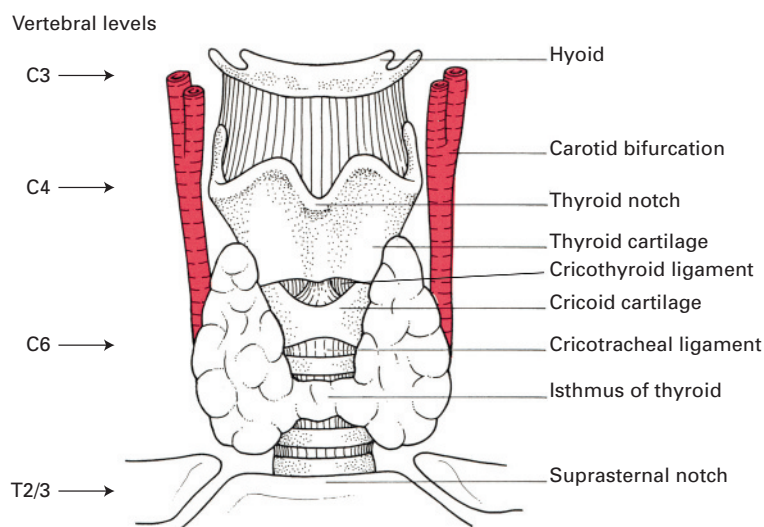
Structurally, the larynx consists of a framework of articulating cartilages, linked together by ligaments, that move in relation to each other by the action of the laryngeal muscles. It lies opposite the 4th, 5th and 6th cervical vertebrae (Fig. 19), separated from them by the laryngopharynx; its greater part is easily palpable, since it is covered superficially merely by the investing deep fascia in the midline and by the thin strap muscles laterally.

The laryngeal cartilages (Figs 20–23)

The principal cartilages are the thyroid, cricoid and the paired arytenoids, together with the epiglottis; in addition, there are the small corniculate and cuneiform cartilages.

The *thyroid cartilage* is shield-like and consists of two laminae that meet in the midline inferiorly, leaving the thyroid notch between them above. This junction is well marked in the male, forming the laryngeal prominence or Adam's apple, but in the female it is not obvious. The laminae

Fig. 19 Anterior view of the larynx to show adjacent important landmarks and vertebral levels.



carry superior and inferior horns, or cornua, at the upper and lower extremities of their posterior borders; the inferior horn bears a circular facet on its inner surface for the cricoid cartilage.

The *cricoid cartilage* is in the shape of a signet ring; the 'signet' lies posteriorly as a quadrilateral lamina joined in front by a thin arch. The side of the lamina bears two articular facets, one for the inferior horn of the thyroid cartilage and the other, near its upper extremity, for the arytenoid cartilage.

The *arytenoid cartilages* are three-sided pyramids that sit one on either side of the superolateral aspect of the lamina of the cricoid. Each has a lateral muscular process, into which are inserted the posterior and lateral cricoarytenoid muscles, and an anterior vocal process, which is the posterior attachment of the vocal ligament.

The *epiglottis* is likened to a leaf. It is attached at its lower tapering end to the back of the thyroid cartilage by means of the thyro-epiglottic ligament. Its superior extremity projects upwards and backwards behind the hyoid and the base of the tongue, and overhangs the inlet of the larynx. The posterior aspect of the epiglottis is free and bears a bulge, termed the *tubercle*, in its lower part. The upper part of the anterior aspect of the epiglottis is also free; its covering mucous membrane sweeps forwards centrally onto the tongue and, on either side, onto the side walls of the oropharynx, to form, respectively, the median glosso-epiglottic and the lateral glosso-epiglottic folds. The valleys on either side of the median glosso-epiglottic fold are termed the *valleculae*; they are common sites for the impaction of sharp swallowed objects such as fish bones.

The lower part of the anterior surface of the epiglottis is attached to the back of the hyoid bone by the hyo-epiglottic ligament. In the neonate, the epiglottis is more deeply furrowed at its free end, and in some babies it

26 The respiratory pathway, lungs, thoracic wall and diaphragm

has a V-shaped appearance on laryngoscopy. The long, deeply grooved, 'floppy' epiglottis of the neonate more closely resembles that of aquatic mammals and is more suited to its function of protecting the nasotracheal air passage during suckling.

The *corniculate cartilage* is a small nodule lying at the apex of the arytenoid.

The *cuneiform cartilage* is a flake of cartilage within the margin of the aryepiglottic fold.

The laryngeal ligaments (Figs 20, 22–24)

The ligaments of the larynx can be divided into the extrinsic and the intrinsic, which link together the laryngeal cartilages.

The extrinsic ligaments are as follows.

- 1 The *thyrohyoid membrane*, which stretches between the upper border of the thyroid cartilage and the hyoid. This membrane is strengthened anteriorly by condensed fibrous tissue, termed the median thyrohyoid ligament, and its posterior margin is also thickened to form the lateral thyrohyoid ligament, stretched between the tips of the greater horn of the hyoid and the upper horn of the thyroid cartilage. The membrane is pierced by the internal branch of the superior laryngeal nerve and by the superior laryngeal vessels.
- 2 The *cricotracheal ligament*, which links the cricoid to the 1st ring of the trachea.
- 3 The *cricothyroid ligament* lies between the thyroid cartilage and the cricoid. It is an easily identified gap in the anterior surface of the laryngeal skeleton through which intratracheal injections may be administered. It is also the recommended site for emergency laryngotomy in cases of laryngeal obstruction (see below).

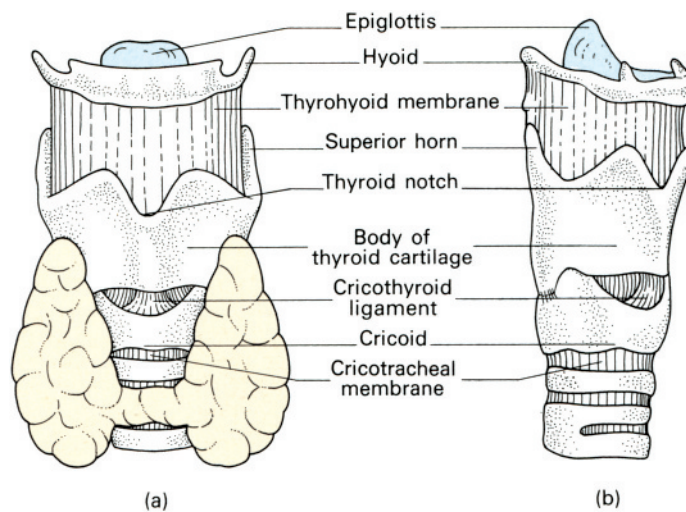


Fig. 20 External views of the larynx: (a) anterior aspect; (b) anterolateral aspect with the thyroid gland and cricothyroid ligament removed.

The larynx 27

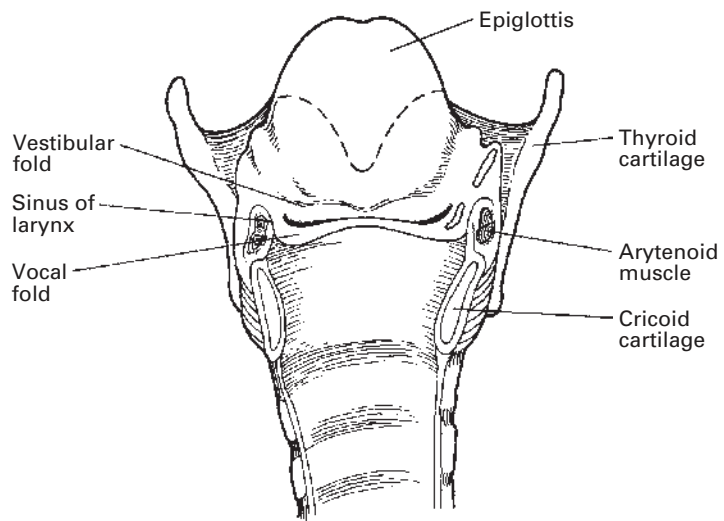


Fig. 21 The larynx dissected from behind, with cricoid cartilage divided, to show the true and false vocal cords with the sinus of the larynx between.

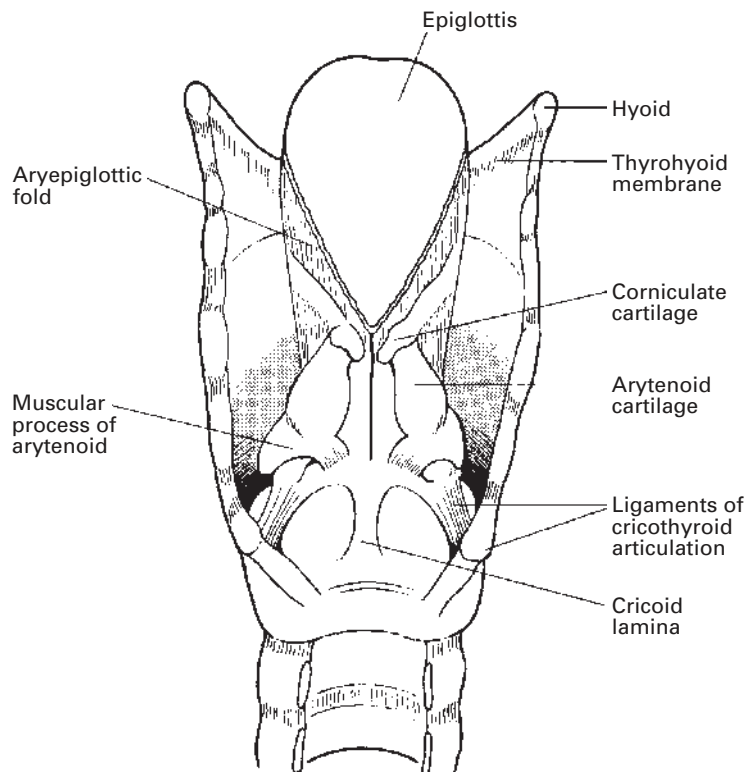


Fig. 22 The cartilages and ligaments of the larynx seen posteriorly.

28 The respiratory pathway, lungs, thoracic wall and diaphragm

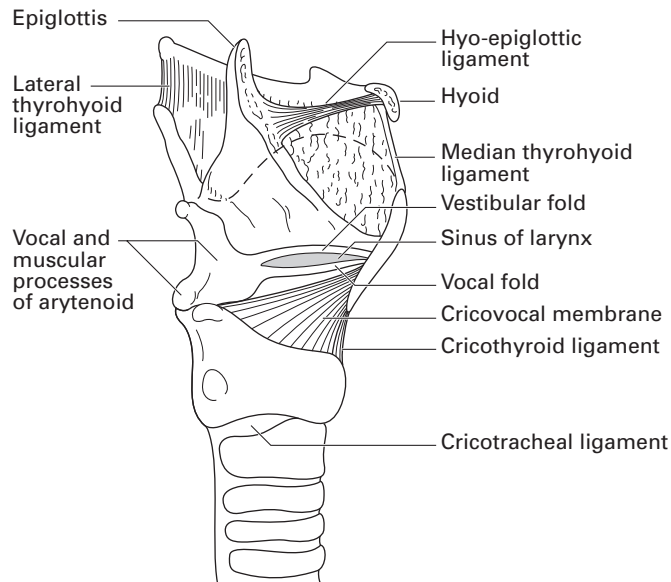


Fig. 23 The cartilages and ligaments of the larynx seen laterally.

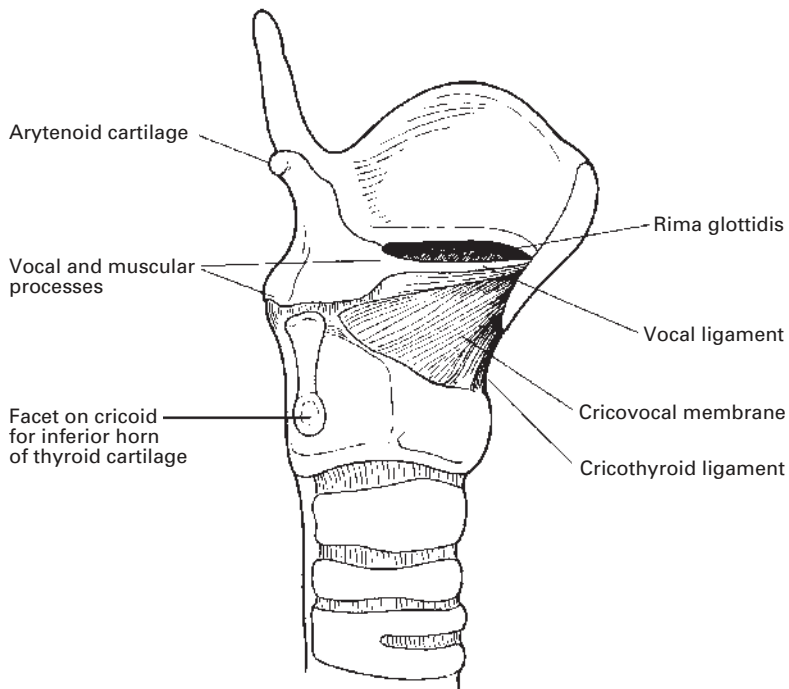


Fig. 24 The formation of the vocal cord and cricovocal membrane.

4 The *hyo-epiglottic ligament*, which connects the epiglottis to the back of the body of the hyoid.

The intrinsic ligaments comprise the capsules of the tiny synovial joints between the arytenoid and cricoid, and between the thyroid and cricoid cartilages, which require no more than this passing mention; more important is the fibrous internal framework of the larynx.

If the cavity of the larynx is inspected in a bisected specimen, two folds will be seen, the upper vestibular and the lower vocal fold (or the *false* and *true vocal cords*), between which is a slit-like recess termed the *sinus* of the larynx (Fig. 21). From the anterior part of the sinus, the *sacculle* of the larynx ascends as a pouch between the vestibular fold and the inner surface of the thyroid cartilage. Beneath the mucosa of the larynx is a sheet of fibrous tissue, divided into an upper and lower part by the sinus. The upper part of the sheet, termed the *quadrangular membrane*, forms the frame of the aryepiglottic fold, which is the fibrous skeleton of the laryngeal inlet; the lower margin of the quadrangular membrane is thickened to form the vestibular ligament, which underlies the vestibular fold, or false vocal cord. The lower sheet of fibrous tissue inferior to the sinus of the larynx contains many elastic fibres and forms the *cricovocal membrane* (Fig. 24). This is attached below to the upper border of the cricoid cartilage, and above is stretched between the mid-point 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 true vocal cord. Anteriorly, the cricovocal membrane thickens into the cricothyroid ligament, which links the cricoid and thyroid in the midline.

CLINICAL NOTE

Tracheostomy, minitracheostomy and cricothyrotomy (cricothyroidotomy)

The performance of a formal tracheostomy requires time and a modicum of surgical skill. However, there are times when incipient or acute supraglottic airway obstruction occurs and an airway needs to be established. The 4th National Audit Project of the Royal College of Anaesthetists reported failure rates of up to 60% for cannula cricothyroidotomy (minitracheostomy) with an almost universal success for emergency surgical airway. It is now recommended that anaesthetists and intensivists should be trained to perform a surgical airway in the form of a dilatational tracheostomy.

Cricothyroidotomy and minitracheostomy

With the patient supine and the neck in the neutral position or, in the absence of cervical spine injury, in extension, the groove between the lower border of the thyroid cartilage and the cricoid cartilage is identified. This groove overlies the cricothyroid ligament. Depending upon the urgency and circumstances local anaesthetic is infiltrated subcutaneously, and a

30 The respiratory pathway, lungs, thoracic wall and diaphragm

1–2 cm horizontal incision is made over the cricothyroid ligament while the larynx is stabilized with the other hand. The ligament can then be incised in a ‘stabbing’ manner with a scalpel. The incision in the membrane can be enlarged by placing the handle of the scalpel into the hole and rotating the scalpel. A small tracheal tube or tracheostomy tube can then be passed through the incision, allowing ventilation of the lungs. Cricothyrotomy is relatively easy to perform and should (in theory at least) be associated with minimal blood loss, as the cricothyroid ligament is largely avascular (Fig. 25).

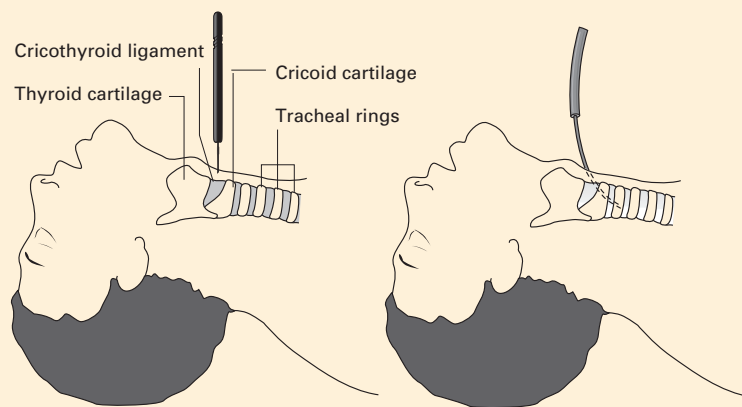


Fig. 25 The site for cricothyroid puncture: the soft area between the thyroid cartilage and the cricoid is easily palpated and is relatively avascular.

Slightly less traumatic is the passage of a small diameter tracheostomy (minitracheostomy) tube using a Seldinger wire-guided technique or using an introducer. The positioning of the patient is the same as for cricothyrotomy but many operators favour a 1 cm vertical incision over the cricothyroid ligament. The membrane may be punctured using a needle and passing a wire, over which an introducer is inserted into the trachea. Alternatively, in some kits, the introducer itself is used to puncture the cricothyroid ligament. A 4.0 mm minitracheostomy tube is then inserted over the introducer as shown in Fig. 26. The minitracheostomy tube may be used for suction therapy for sputum retention, for O₂ therapy and as an emergency airway (for upper airway obstruction). In the UK, minitracheostomies are no longer used for ventilation.

Tracheostomy

The anterior relations of the cervical portion of the trachea are naturally of prime importance in performing a tracheostomy. It is important to keep the head fully extended with a sandbag placed between the patient's shoulders, and to maintain the head absolutely straight with the chin and sternal notch in a straight line. From the cosmetic point of view, it is better to use a

short transverse incision placed midway between the cricoid cartilage and the suprasternal notch. The tyro may find in an emergency, however, that it is safer to use a vertical incision that passes from the lower border of the thyroid cartilage to just above the suprasternal notch.

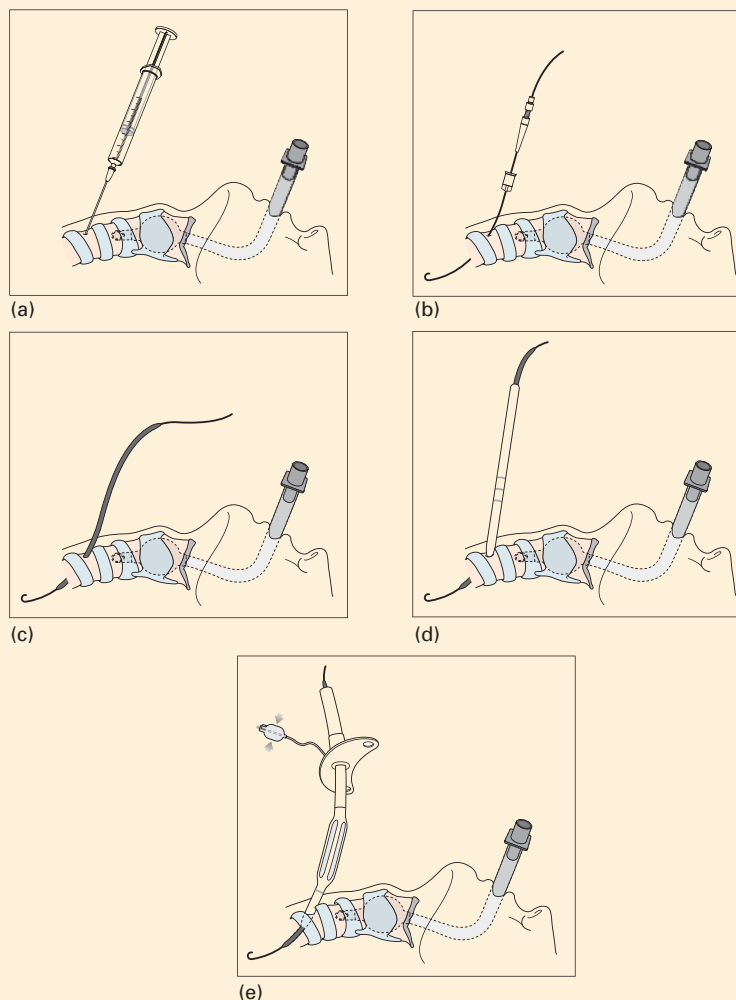


Fig. 26 Percutaneous tracheostomy. (a) Needle puncture below the first tracheal ring. (b) Insertion of a Seldinger wire. (c and d) Serial dilation of the aperture using bougies. (e) Insertion of the endotracheal tube.

The great anatomical and surgical secret of the operation is to keep exactly to the midline; in doing so, the major vessels of the neck are out of danger. The skin incision is deepened to the investing layer of fascia, which is split vertically, thus separating the pretracheal muscles on either side. These are held apart by retractors. The 1st ring of the trachea now comes into view, and the position of the trachea can be checked carefully by

32 The respiratory pathway, lungs, thoracic wall and diaphragm

palpating its rings. It is often possible to push the isthmus of the thyroid gland downwards to expose the upper rings of the trachea; if not, the isthmus is lifted up by blunt dissection and divided vertically between artery forceps. The trachea is opened by a small vertical incision (Fig. 27). A tracheostomy tube of the largest size that will fit the tracheostome comfortably is inserted, the trachea is aspirated through it and the wound is loosely closed with two or three skin sutures.

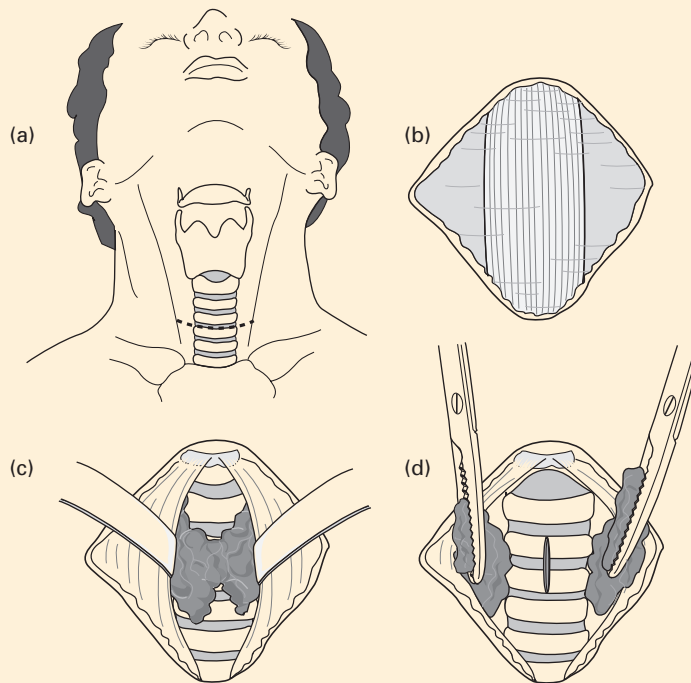


Fig. 27 Tracheostomy: (a) the incision is placed midway between the cricoid cartilage and the suprasternal notch. (b) The investing layer of fascia covering the pretracheal muscles is exposed. (c) The isthmus of the thyroid is cleared. This must either be divided between artery forceps or displaced downwards. (d) A vertical incision is made in the trachea.

Percutaneous tracheostomy

Percutaneous tracheostomy (Fig. 26) is now the tracheostomy method of choice on most intensive care units (ICUs). It may be performed by appropriately trained intensivists and is performed in the ICU rather than in the operating theatre. There are a variety of kits that work by progressive bougie dilatation or by balloon dilatation over a Seldinger wire inserted below the 1st tracheal ring under bronchoscopic control. The results of this new technique have been excellent and it is associated with fewer complications, in both the long and short term. The scarring is usually small and the

cosmetic result satisfactory. Formal surgical tracheostomy is the preserve of the ENT surgeons and is reserved on the ICU for patients with difficult anatomy in whom there is a perceived risk of vascular damage or damage to the thyroid.

With the patient in the supine position and the neck extended, the cricoid cartilage is identified. The tracheal rings immediately below the cricoid cartilage are palpated. The space between the 1st and 2nd tracheal ring is most commonly used. Local anaesthetic, which may contain epinephrine in low concentration, is injected if necessary. A 1 cm incision is made over the trachea and a needle mounted on a syringe is passed through the tracheal wall between the cartilaginous rings. Aspiration of air confirms correct tracheal placement, and a wire is then passed through the needle into the trachea. The needle is withdrawn. This wire acts as a guide for a series of dilators, or a balloon dilator, that enlarge the hole in the trachea sufficiently to allow the passage of a tracheostomy tube. Great care must be exercised to ensure adequate ventilation and oxygenation during the performance of a percutaneous tracheostomy. This technique is currently accepted as the standard technique for longer term airway management in many ICUs.

The muscles of the larynx

The muscles of the larynx can be divided into the extrinsic group, which attach the larynx to its neighbours, and the intrinsic group, which are responsible for moving the cartilages of the larynx one against the other.

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

- 1 The *sternothyroid muscle* stretches from the posterior aspect of the manubrium to the oblique line on the lateral surface of the thyroid lamina. It is supplied by the ansa hypoglossi (see page 291) and depresses the larynx.
- 2 The *thyrohyoid muscle* passes upwards from the oblique line of the thyroid lamina to the inferior border of the greater horn of the hyoid. It is supplied by fibres of C1 conveyed through the hypoglossal nerve (see page 290). It elevates the larynx.
- 3 The *inferior constrictor* arises from the oblique line of the thyroid lamina, from a tendinous arch over the cricothyroid muscle and from the side of the pharynx. This muscle acts solely as a constrictor of the pharynx and is considered fully with this structure (see page 20).

Other muscles play an important part in movements of the larynx indirectly, via its close attachment, by ligaments and muscle, with the hyoid bone. These muscles help to elevate and depress the larynx; the indirect elevators are the mylohyoid, stylohyoid and geniohyoid, and the indirect depressors are the sternohyoid and omohyoid.

The *intrinsic muscles* of the larynx (Figs 28, 29) have a threefold function: they open the cords in inspiration, they close the cords and the

34 The respiratory pathway, lungs, thoracic wall and diaphragm

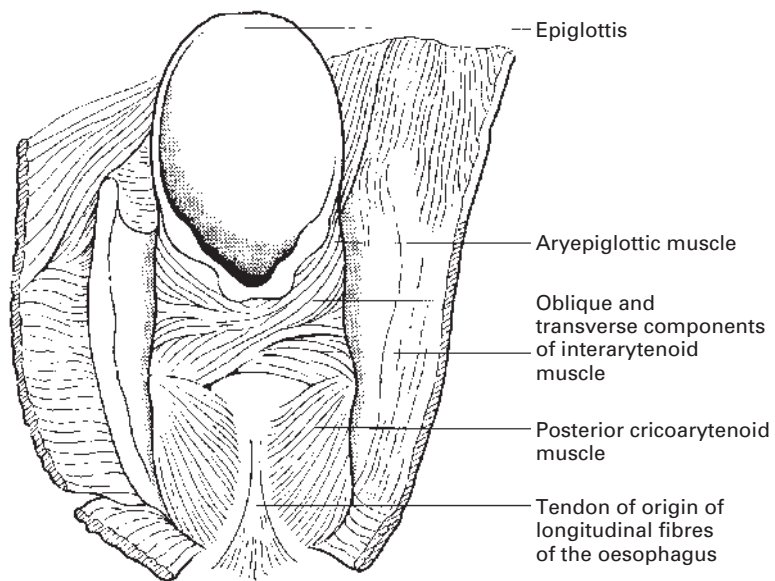


Fig. 28 The intrinsic muscles of the larynx.

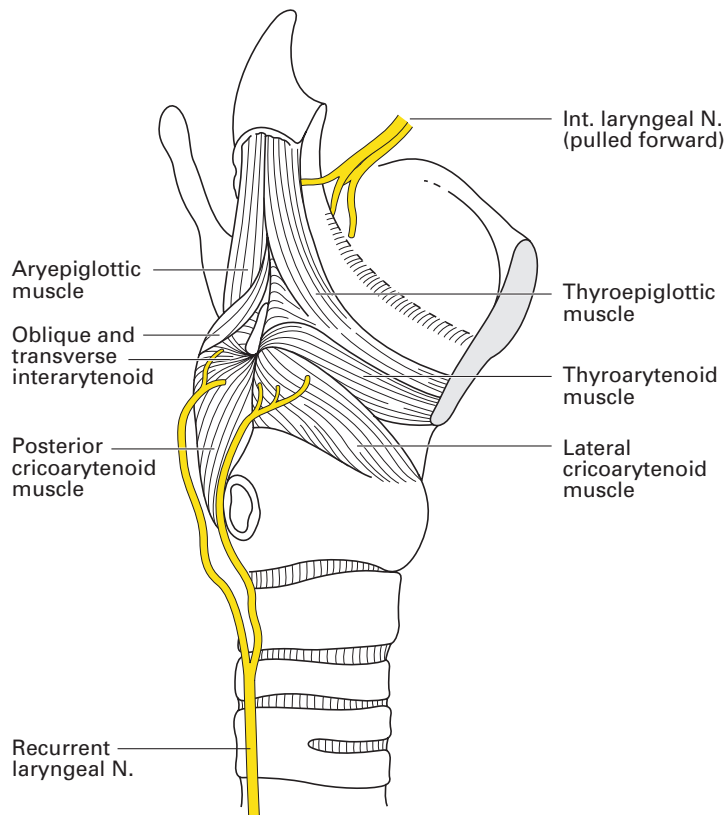


Fig. 29 The intrinsic muscles of the larynx, lateral view.

The larynx 35

laryngeal inlet during deglutition, and they alter the tension of the cords during speech. They comprise the posterior and lateral cricoarytenoids, the interarytenoids and the aryepiglottic, the thyroarytenoid, the thyroepiglottic, the vocalis and the cricothyroid muscles.

- 1 The *posterior cricoarytenoid* muscle arises from the posterior surface of the lamina of the cricoid and is inserted into the posterior aspect of the muscular process of the arytenoid. It abducts the cord by external rotation of the arytenoid and thus opens the glottis; it is the only muscle to do so.
- 2 The *lateral cricoarytenoid* muscle arises from the superior border of the arch of the cricoid and is inserted into the lateral aspect of the arytenoid cartilage. It adducts the cord by internally rotating the arytenoid cartilage, thus closing the glottis.
- 3 The *interarytenoid* muscle, the only unpaired muscle of the larynx, runs between the two arytenoid cartilages. Its action is to help close the glottis, particularly its posterior part. The muscle is made up of transverse and oblique fibres; the latter continue upwards and outwards as the *aryepiglottic* muscle, which lies within the aryepiglottic fold and acts as a rather feeble sphincter to the inlet of the larynx.
- 4 The *thyroarytenoid* muscle has its origin from the posterior aspect of the junction of the laminae of the thyroid cartilage and is inserted into the arytenoid cartilage on its anterolateral aspect, from the tip of its vocal process back onto its muscular process. By drawing the arytenoid forwards, this muscle serves to shorten, and thus relax, the vocal cord. Some fibres of this muscle continue in the aryepiglottic fold to the margin of the epiglottis, forming the *thyro-epiglottic* muscle, which assists in the sphincter mechanism of the laryngeal inlet.
- 5 The *vocalis* is simply some muscle fibres of the deep aspect of the thyroarytenoid that are inserted into the vocal fold. It may function as an adjusting mechanism to the tension of the cord.
- 6 The *cricothyroid*, the only intrinsic laryngeal muscle that lies outside the cartilaginous framework, arises from the anterior part of the outer aspect of the arch of the cricoid cartilage. Its fibres pass upwards and backwards to become inserted into the inferior border of the lamina of the thyroid cartilage and along the anterior face of its inferior cornu. Contraction of this muscle elevates the anterior part of the arch of the cricoid, approximating it to the thyroid cartilage. The effect of this is to tilt the lamina of the cricoid, bearing with it the arytenoid, posteriorly, thus lengthening the anteroposterior diameter of the glottis and thus, in turn, putting the vocal cords on stretch (Fig. 30). This muscle is the only tensor of the cord.

The actions of the intrinsic laryngeal muscles can be summarized thus:

- 1 abductors of the cords: posterior cricoarytenoids;
- 2 adductors of the cords: lateral cricoarytenoids, interarytenoid;
- 3 sphincters to vestibule: aryepiglottics, thyro-epiglottics;
- 4 regulators of cord tension: cricothyroids (tensors), thyroarytenoids (relaxors), vocales (fine adjustment).

36 The respiratory pathway, lungs, thoracic wall and diaphragm

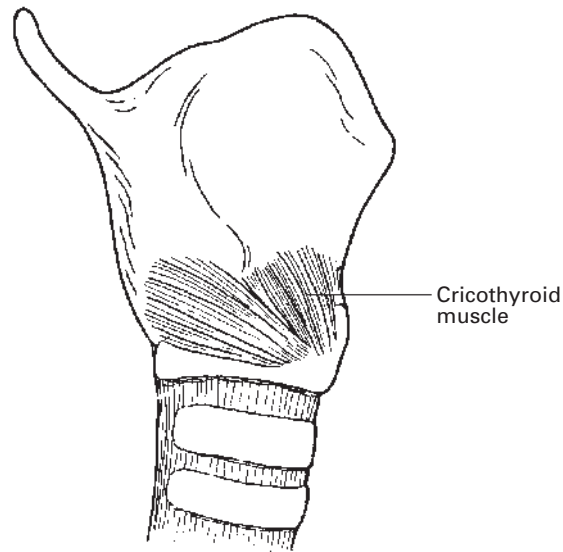


Fig. 30 The cricothyroid muscle.

Blood supply

The *superior laryngeal artery* is a branch of the superior thyroid artery, which is the 1st branch of the external carotid. It accompanies the internal branch of the superior laryngeal nerve and in its company pierces the thyrohyoid membrane to supply the interior of the larynx.

The *inferior laryngeal artery* arises from the inferior thyroid branch of the thyrocervical trunk, which, in turn, arises from the first part of the subclavian artery. It accompanies the recurrent laryngeal nerve into the larynx. The corresponding veins drain into the superior and inferior thyroid veins. Thus, the blood supply of the larynx comes from the superior and inferior laryngeal arteries and veins, which are derived from the superior and inferior thyroid vessels and which accompany the superior and 'inferior' (recurrent) laryngeal nerves, respectively.

Lymph drainage

The lymphatics of the larynx are separated into an upper and lower group by the vocal cords. The supraglottic area is drained by vessels that accompany the superior laryngeal vein and empty into the upper deep cervical lymph nodes. The infraglottic zone similarly drains in company with the inferior vein into the lower part of the deep cervical chain. Lymphatics from the anterior part of the lower larynx also empty into small prelaryngeal and pretracheal nodes.

The vocal cords themselves are firmly bound down to the underlying vocal membrane; lymph channels are therefore absent in this region, which accounts for the clearly defined watershed between the upper and lower zones of lymph drainage.

Nerve supply

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

The *superior laryngeal nerve* passes deep to both the internal and external carotid arteries and there divides into a small external branch, which supplies the cricothyroid muscle, and a larger internal branch, which pierces the thyrohyoid membrane to provide the sensory supply to the interior of the larynx as far down as the vocal cords; it probably also sends motor fibres to the interarytenoid muscle.

The *internal laryngeal nerve* runs beneath the mucosa of the piriform fossa. In this position it can easily be blocked by the topical application of local anaesthetic to provide anaesthesia for laryngoscopy and bronchoscopy.

The *recurrent laryngeal nerve* on the right side leaves the vagus as the latter crosses the right subclavian artery; it 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; the nerve then passes under the arch to reach the groove between the oesophagus and the trachea. Once it reaches the neck, the left nerve assumes the same relationships as on the right (see Fig. 37). The recurrent laryngeal nerves provide the motor supply to the intrinsic muscles of the larynx apart from cricothyroid, as well as the sensory supply to the laryngeal mucosa inferior to the vocal cords.

Injuries of the laryngeal nerves

There is an intimate and important relationship between the nerves that supply the larynx and the vessels that supply the thyroid gland. The external branch of the superior laryngeal nerve descends over the inferior constrictor muscle of the pharynx immediately deep to the superior thyroid artery and vein as these pass to the superior pole of the gland; at this site the nerve may be damaged in securing these vessels. Since this nerve supplies the cricothyroid muscle, the sole tensor muscle of the vocal cord and hence described as the 'tuning fork of the larynx', its damage will be followed by hoarseness. This, fortunately, is temporary and becomes compensated by increased action of the opposite cricothyroid.

The recurrent laryngeal nerve, as it ascends in the tracheo-oesophageal groove, is overlapped by the lateral lobe of the thyroid gland, and here comes into close relationship with the inferior thyroid artery as this 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 (Fig. 31). 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. Injury to the recurrent nerve is an obvious hazard of thyroidectomy, especially since the nerve may be displaced from its normal anatomical location by a diseased thyroid gland.

38 The respiratory pathway, lungs, thoracic wall and diaphragm

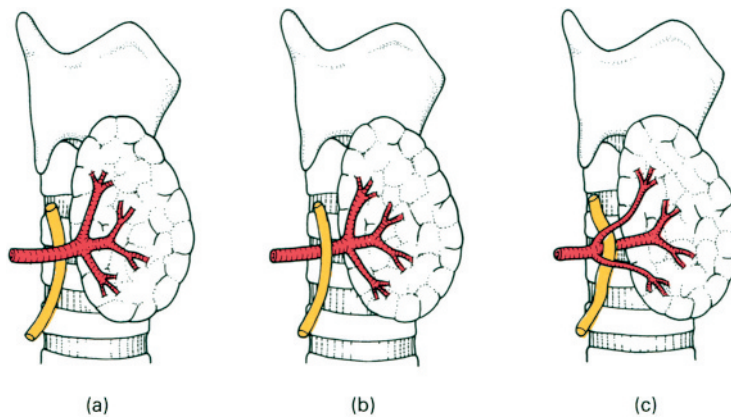


Fig. 31 The relationship between the recurrent laryngeal nerve and the inferior thyroid artery. The nerve may (a) cross posteriorly to the artery, (b) be anterior to or (c) pass through the branches of the artery. In this diagram, the lateral lobe of the thyroid is pulled forwards as it would be during thyroidectomy.

Recurrent laryngeal nerve paralysis may occur not only as a result of injury at thyroidectomy but also from involvement of the nerve by a malignant or occasionally benign enlargement of the thyroid gland, by enlarged lymph nodes or by cervical trauma. The left nerve may be involved in its thoracic course by malignant tumours of the lung or oesophagus, malignant or inflamed nodes, by an aneurysm of the aortic arch or even, in mitral stenosis, by compression between the left pulmonary artery (pushed upwards by the greatly enlarged left atrium) and the aortic arch. It is occasionally injured in performing a ligation of a patent ductus arteriosus, since the nerve lies immediately deep to the ductus as it hooks beneath the aortic arch (see Fig. 82a).

It is not surprising that the left recurrent nerve, whose intrathoracic course brings it into relationship with many additional structures, should be paralysed twice as often as the right. Some 25% of all recurrent nerve palsies, it should be noted, are idiopathic; they probably result from a peripheral neuritis.

Damage to the recurrent laryngeal nerve results in paralysis of the corresponding cord, which lies motionless, near the midline and at a lower level than the opposite side – the last being due to the downward drag of the paralysed muscles. Unilateral paralysis produces a slight hoarseness that usually disappears as a result of compensatory overadduction of the opposite normal cord. However, bilateral paralysis results in complete loss of vocal power. Moreover, the two paralysed cords flap together, producing a valve-like obstruction, especially during inspiration, with incapacitating dyspnoea and marked inspiratory stridor.

Respiratory obstruction after thyroidectomy can also result from direct trauma to the tracheal cartilages (especially in carcinoma of the thyroid) causing tracheomalacia. It may be the result of haemorrhage into the neck deep to the investing fascia, causing external pressure on the trachea. In practice, provided that the tracheal cartilages have not been damaged, it is very unusual for a benign enlarged thyroid gland to compress the trachea to an extent that prevents tracheal intubation. The trachea invariably straightens and dilates during intubation. Similarly, haemorrhage into an

intact gland is more likely to obstruct the airway by producing laryngeal oedema than by compression of the intact trachea. However, following thyroidectomy, when the fascial planes have been disturbed, bleeding may compress the trachea and compromise the airway by both tracheal compression and laryngeal oedema.

It is of note that laryngoscopy within 24 hours of thyroidectomy often reveals some degree of oedema of the false cords, presumably as a result of external laryngeal trauma during the operation and damage to venous and lymphatic drainage channels.

CLINICAL NOTE

Laryngoscopic anatomy

To view the larynx at direct laryngoscopy and then to pass a tracheal tube depends on getting the mouth, the oropharynx and the larynx into one plane. Flexion of the neck brings the axes of the oropharynx and the larynx in line but the axis of the mouth still remains at right angles to the others; their alignment is achieved by full extension of the head at the atlanto-occipital joint. This is the position, with the nose craning forwards and upwards, that the anaesthetist assumes in sniffing the fresh air after a long day in the operating theatre, or in moving the head forwards to take the first sip from a pint of beer that is full to the brim.

At laryngoscopy, the anaesthetist first views the base of the tongue, the valleculae and the anterior surface of the epiglottis. The laryngeal aditus then comes into view (Fig. 32), bounded in front by the posterior aspect of the epiglottis, with its prominent epiglottic tubercle. The aryepiglottic folds are seen on either side running posteromedially from the lateral aspects of the epiglottis; they are thin in front but become thicker as they pass backwards where they contain the cuneiform and corniculate cartilages. The vocal cords appear as pale, glistening ribbons that extend from the angle of the thyroid cartilage backwards to the vocal processes of the arytenoids. Between the cords is the triangular (apex forwards) opening of the rima glottidis, through which can be seen the upper two or three rings of the trachea.

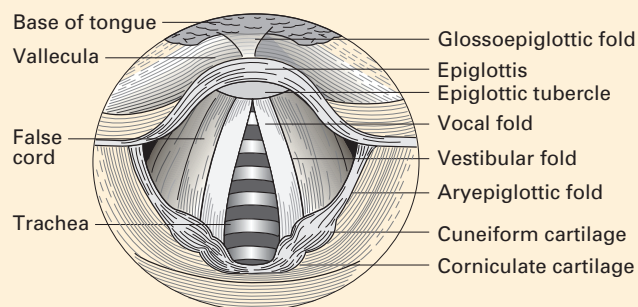


Fig. 32 View of the larynx at laryngoscopy.

40 The respiratory pathway, lungs, thoracic wall and diaphragm

Difficulties in tracheal intubation

Certain anatomical characteristics may make oral tracheal intubation difficult. This is particularly so in the patient with a poorly developed mandible and receding chin, especially in those subjects in which this is associated with a short distance between the angle of the jaw and the thyroid cartilage. A sagittal section through the head (Fig. 33) shows that the epiglottis becomes 'tucked under' the bulging tongue, and great difficulty is experienced in such instances in inserting the blade of the laryngoscope into the vallecula.

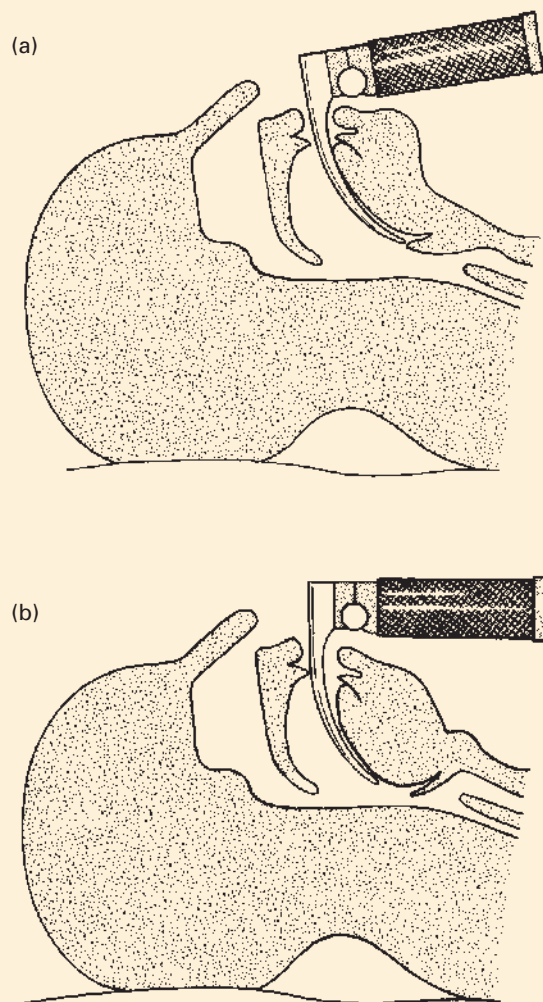


Fig. 33 (a) The position of the laryngoscope in the normal patient. (b) The problem presented by the receding chin and poorly developed mandible.

Views of the larynx at laryngoscopy can be graded for purposes of assessment and record-keeping. The most popular grading system in current use is that described by Cormack and Lehane (Fig. 34).

A variety of scoring systems have been devised that aim to predict difficulties with laryngoscopy and intubation. The Mallampati score makes an anatomical assessment of the likely degree of difficulty of tracheal intubation based on the structures that can be seen when the patient opens his or her mouth fully (Fig. 35).

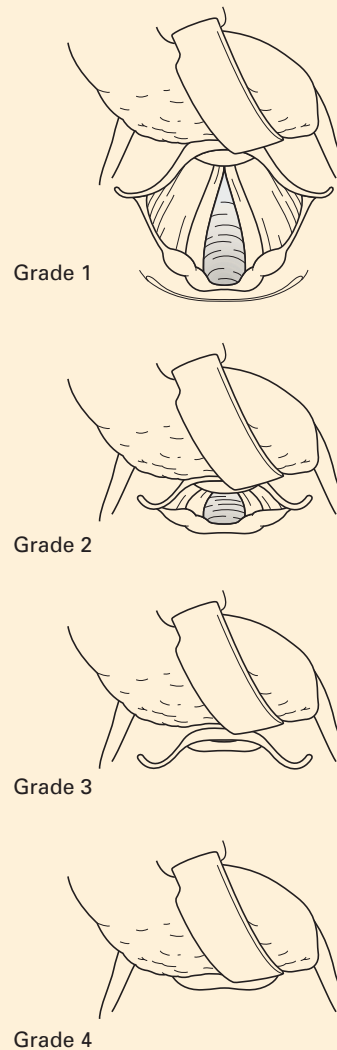
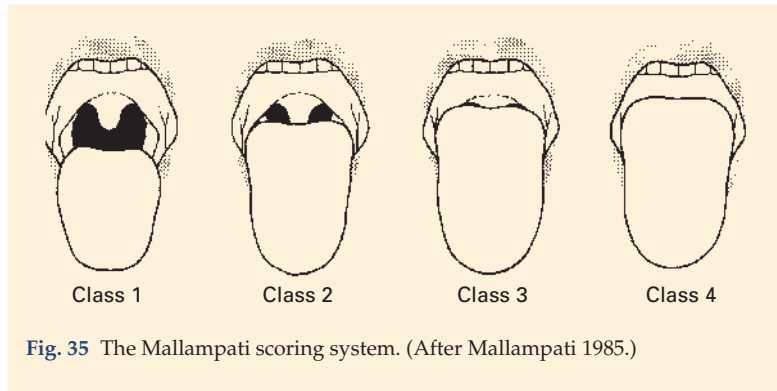


Fig. 34 The Cormack and Lehane laryngoscopy grading system. Grade 1, all structures are visible. Grade 2, only the posterior part of the glottis is visible. Grade 3, only the epiglottis is seen. Grade 4, no recognizable structures.

42 The respiratory pathway, lungs, thoracic wall and diaphragm



Structure

The mucosa of the larynx is mainly a ciliated columnar epithelium with scattered mucus-secreting goblet cells. This epithelium becomes stratified squamous at two sites – over the vocal folds and at the entrance to the larynx where this is in continuity with the food passage, i.e. over the anterior aspect of the epiglottis, the upper part of its posterior aspect and the upper part of the aryepiglottic folds.

The mucosa also contains numerous mucous glands, particularly over the epiglottis. Here, these glands excavate the little pits that become obvious when the mucous membrane is stripped away from the epiglottic cartilage. The glands are absent, however, over the vocal folds, where the epithelium is adherent to the underlying vocal ligament.

The trachea

The trachea extends from its attachment to the lower end of the cricoid cartilage, at the level of the 6th cervical vertebra, to its termination at the bronchial bifurcation. In the preserved dissecting-room cadaver, this is at the level of the 4th thoracic vertebra and the manubriosternal junction (the angle of Louis); in the living subject in the erect position, the lower end of the trachea can be seen in oblique radiographs of the chest to extend to the level of the 5th, or in full inspiration the 6th, thoracic vertebra.

In the adult, the trachea is some 15 cm long, of which 5 cm lie above the suprasternal notch; this portion is somewhat greater (nearly 8 cm) when the neck is fully extended. The diameter of the trachea is correlated with the size of the subject; a good working rule is that it has the same diameter as the patient's index finger.

The patency of the trachea is maintained by a series of 16–20 C-shaped cartilages joined vertically by fibro-elastic tissue and closed posteriorly by the non-striated trachealis muscle. The cartilage at the tracheal bifurcation is the keel-shaped *carina* (Fig. 36), which is seen as a very obvious sagittal ridge when the trachea is inspected bronchoscopically. Should the sharp

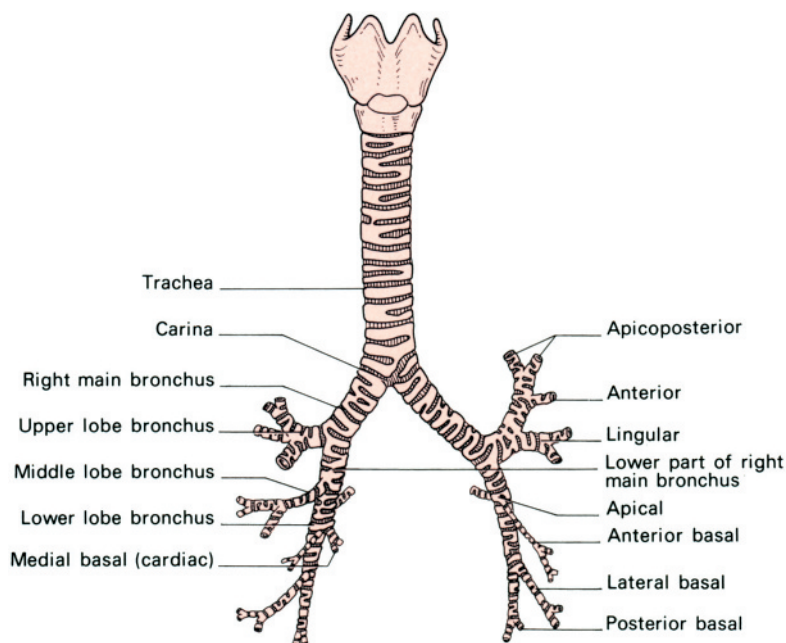


Fig. 36 The trachea and main bronchi viewed from the front.

edge of the carina become flattened, this usually denotes enlargement of the hilar lymph nodes or gross distortion of the pulmonary anatomy by fibrosis, tumour or other pathology.

Relations

The trachea lies exactly in the midline in the cervical part of its course, but within the thorax it is deviated slightly to the right by the arch of the aorta.

In the *neck* (Fig. 37), it is covered anteriorly by the skin and by the superficial and deep fascia, through which the rings are easily felt. The 2nd to the 4th rings are covered by the isthmus of the thyroid where, along the upper border, branches of the superior thyroid artery join from either side. In the lower part of the neck, the edges of the sternohyoid and sternothyroid muscles overlap the trachea, which here is also covered by the inferior thyroid veins (as they stream downwards to the brachiocephalic veins), by the cross-communication between the anterior jugular veins and, when present, by the thyroidea ima artery, which ascends from the arch of the aorta or from the brachiocephalic artery. It is because of this close relationship with the brachiocephalic artery that erosion of the tracheal wall by a tracheostomy tube may cause sudden profuse haemorrhage. It is less common for the carotid artery to be involved in this way. On either side are the lateral lobes of the thyroid gland, which intervene between the trachea and the carotid sheath and its contents (the common carotid artery, the internal jugular vein and the vagus nerve). Posteriorly, the trachea rests on the oesophagus, with the recurrent laryngeal nerves lying on either side in a groove between the two.

44 The respiratory pathway, lungs, thoracic wall and diaphragm

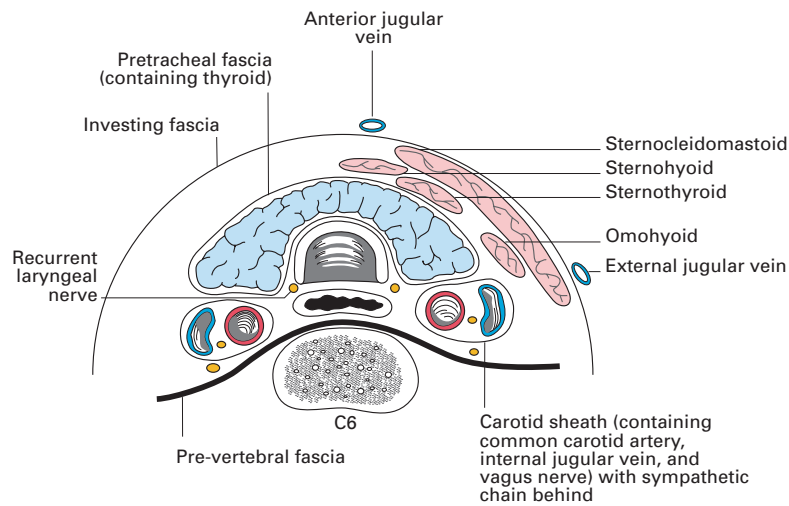


Fig. 37 Transverse section of the neck through C6.

The close relationship of the unsupported posterior tracheal wall and the oesophagus is revealed during oesophagoscopy. When a tracheal tube with an inflated cuff is in the trachea, the anterior wall of the oesophagus is compressed. For this reason, patients with inflated tracheostomy tubes (especially high-pressure cuffs) may have difficulty in swallowing. During oesophagoscopy with a rigid oesophagoscope, an overinflated tracheal tube cuff may be mistaken for an oesophageal obstruction.

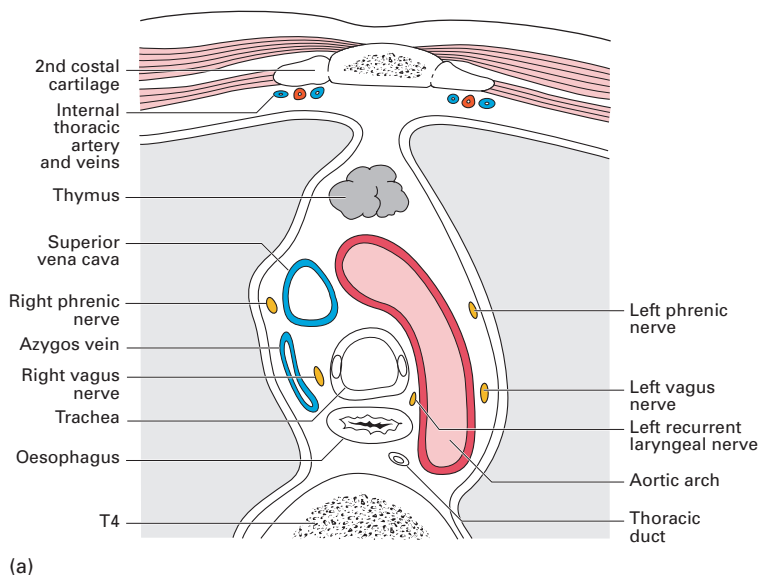
Because the trachea is a superficial structure in the neck, it is possible to feel the bulge caused by the rapid injection of 5 ml of air into the cuff of an accurately placed tracheal tube. This is detected by placing two fingers over the trachea above the suprasternal notch.

The *thoracic* part of the trachea (Fig. 38) descends through the superior mediastinum. Anteriorly, from above downwards, lie the inferior thyroid veins, the origins of the sternothyroid muscles from the back of the manubrium, the remains of the thymus, the brachiocephalic artery and the left common carotid artery – which separate the trachea from the left brachiocephalic vein – and, lastly, the arch of the aorta. Posteriorly, as in its cervical course, the trachea lies throughout on the oesophagus, with the left recurrent laryngeal nerve placed in a groove between the left borders of these two structures (Fig. 39).

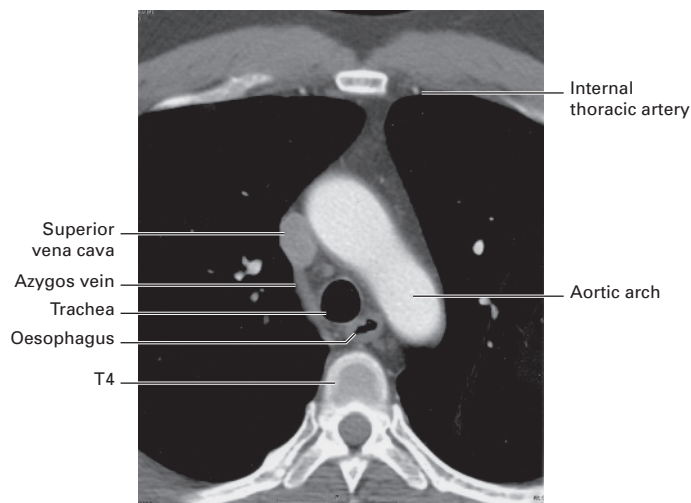
On the right side, the trachea is in contact with the mediastinal pleura, except where it is separated by the azygos vein and the right vagus nerve. On the left, the left common carotid and left subclavian arteries, the aortic arch and the left vagus intervene between the trachea and the pleura; the altering relationships between the major arteries and the trachea are the result of the diverging, somewhat spiral, course of the arteries from their aortic origins to the root of the neck.

The large tracheobronchial lymph nodes lie at the sides of the trachea and in the angle between the two bronchi.

The trachea 45



(a)



(b)

Fig. 38 The thoracic trachea and its environs in a transverse section through the 4th thoracic vertebra. (a) Diagrammatic. (b) Computerized tomography at T4.

In *infants*, these relationships are somewhat modified; 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 – a frightening encounter if found tensely distended with blood when performing a tracheotomy on an asphyxiating baby. In children up to the age of 2 years, the thymus is large and lies in front of the lower part of the cervical trachea.

46 The respiratory pathway, lungs, thoracic wall and diaphragm

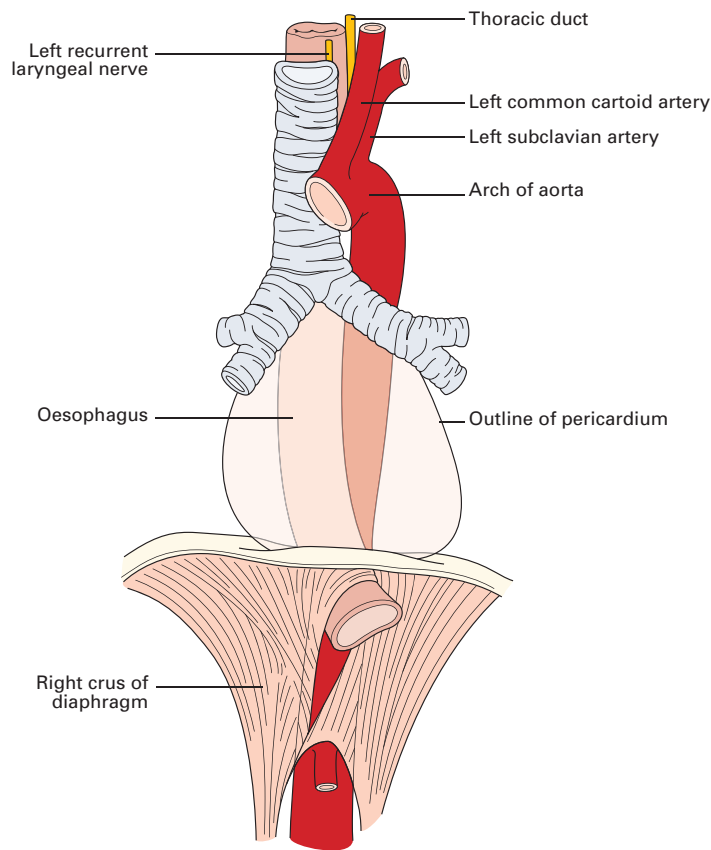


Fig. 39 The trachea and its immediate relations.

Vascular, lymphatic and nerve supply

The arterial supply to the trachea is derived from the inferior thyroid arteries and the venous drainage is via the inferior thyroid veins. Lymphatics pass to the deep cervical, pretracheal and paratracheal nodes. The trachea is innervated by the recurrent laryngeal branch of the vagus with a sympathetic supply from the middle cervical ganglion.

The main bronchi

The trachea bifurcates in the supine cadaver at the level of the 4th thoracic vertebra into the right and left bronchi. In the erect position in full inspiration in life, the level of bifurcation is at T6.

The *right main bronchus* (Fig. 36) is shorter, wider and more vertically placed than the left: shorter because it gives off its upper lobe bronchus sooner (after a course of only 2.5 cm); wider because it supplies the larger lung; and more vertically placed (at 25° to the vertical compared with 45° on the left) because the left bronchus has to extend laterally behind the

The main bronchi 47

aortic arch to reach its lung hilum. Obviously, inhaled foreign bodies or a bronchial aspirating catheter are far more inclined to enter the wider and more vertical right bronchus than the narrower and more obliquely placed left.

The right pulmonary artery is first below and then in front of the right main bronchus, and the azygos vein arches over it.

The *left main bronchus* (Figs 36, 39) is 5 cm long. It passes under the aortic arch, in front of the oesophagus, thoracic duct and descending aorta, and has the left pulmonary artery lying first above and then in front of it.

CLINICAL NOTE**Endobronchial tubes**

Because the right upper lobe bronchus arises only a short distance below the carina, it is not possible to place a tube in that bronchus without the risk of obstruction of the lower lobe. To overcome this difficulty, right-sided endobronchial tubes have an orifice in the lateral surface of the tube that coincides with the opening of the right upper lobe (Fig. 40). No special arrangement has to be made for tubes placed in the left bronchus, as the 5 cm distance between the carina and the left upper lobe bronchus leaves ample room for the cuffed end of an endobronchial tube. The position of the tube is routinely checked by fibre-optic bronchoscopy.

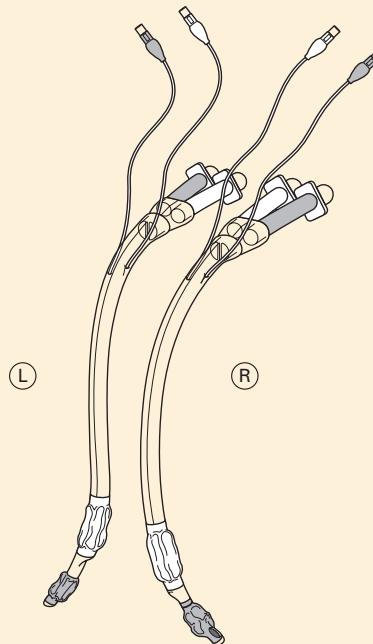


Fig. 40 Left and right double-lumen endobronchial tubes. Note the fenestration in the area of the distal cuff on the right-side tube.

48 The respiratory pathway, lungs, thoracic wall and diaphragm

The pleura

Each lung, in its development, invaginates the coelomic cavity to form a double-walled serous-lined sac – the pleura. The pleura comprise a *visceral layer*, which invests the lung itself and passes into its fissures, and a *parietal layer*, which clothes the diaphragm, the chest wall, the apex of the thorax and the mediastinum. The two layers meet at the site of invagination, which is the lung root or *hilum*, and here the pleura hang down as a fold, rather like an empty sleeve, termed the *pulmonary ligament*. Between the two layers of the pleura is a potential space, the *pleural cavity*, which is moistened with a film of serous fluid.

The visceral pleura is closely adherent to the surface of the underlying lung; attempts to strip the pleura will tear into the lung parenchyma. In contrast, the parietal pleura is separated from the overlying chest wall by a thin layer of loose connective tissue, the *extrapleural fascia*, which enables the surgeon to strip the parietal pleura freely and bloodlessly from the chest wall.

The lines of pleural reflection (Figs 41, 42)

The pleural margins can be mapped out on the chest wall as follows.

- 1 The apex of the pleura extends about 4 cm above the medial third of the clavicle.
- 2 The margin then passes behind the sternoclavicular joint and meets the opposite pleural edge behind the sternum at the 2nd costal cartilage level (the angle of Louis).
- 3 At the 4th cartilage, the left pleura deflects to the lateral margin of the sternum, corresponding to the cardiac notch of the underlying lung, and descends thence to the 6th costal cartilage.

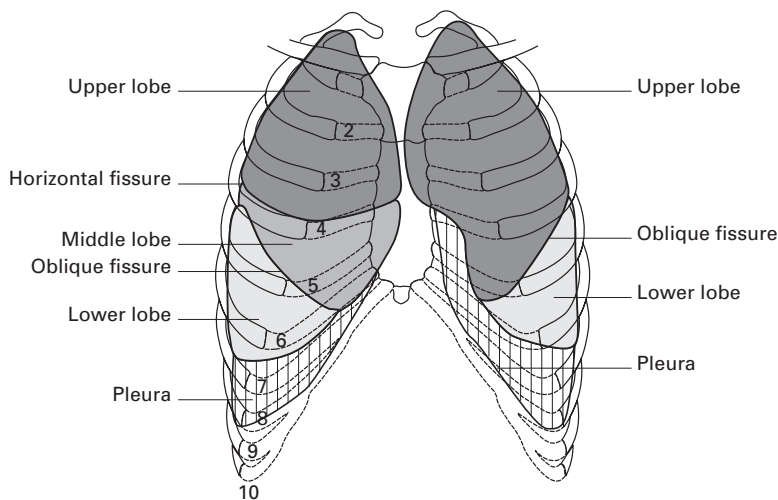


Fig. 41 The surface markings of the lungs and pleura, anterior view.

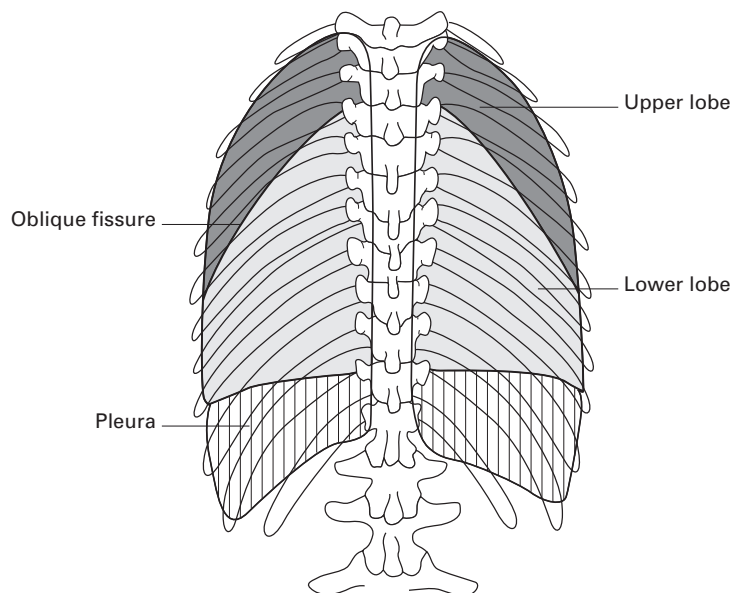


Fig. 42 The surface markings of the lungs and pleura, posterior view.

- 4 The right pleural edge continues vertically downwards and projects a little below the right costo-xiphoid angle.
- 5 The pleural lower margin is easily remembered; it lies at the level of the 8th rib in the mid-clavicular line and at the level of the 10th rib at the mid-axillary line (here at its lowest level), and terminates behind at the level of the spine of the 12th thoracic vertebra, descending posteriorly slightly below the costal margin at the costo-vertebral angle.

The inferior margin of the parietal pleura does not extend to the line of attachment of the diaphragm to the chest wall; here, the muscle of the diaphragm comes into direct contact with the lowermost costal cartilages and intercostal spaces. Moreover, the lung in quiet respiration does not fill the lowermost extremity of the pleural sac, but leaves the slit-like *costo-diaphragmatic recess* where the costal and diaphragmatic pleurae are in contact. This recess provides a reserve sinus which the lung invades in forced inspiration; it may be opened inadvertently in operations performed below, or through the bed of, the 12th rib, notably during exposure of the kidney or the suprarenal gland.

CLINICAL NOTE

Chest tube insertion (Fig. 43)

Drainage of air or liquids such as blood from the pleura often requires the placement of a chest drain/tube. The British Thoracic Society recommends that, when inserting a drain for fluid drainage, ultrasonic guidance be used to identify loculations and pleural thickening. Real-time scanning improves safety as the diaphragm can be identified during respiration. In extreme

50 The respiratory pathway, lungs, thoracic wall and diaphragm

circumstances, this may not be possible or feasible. Insertion should be in the safe triangle as shown in Fig. 44. This is the triangle bordered by the anterior border of latissimus dorsi, the lateral border of the pectoralis major muscle, a horizontal line corresponding to the 5th intercostal space and an apex below the axilla. The hand of the affected side is placed behind the head to expose the area. After identification of the correct site of placement, local anaesthetic (lidocaine with epinephrine up to 3 mg/kg) is infiltrated subcutaneously if necessary and a small incision is made in the skin.

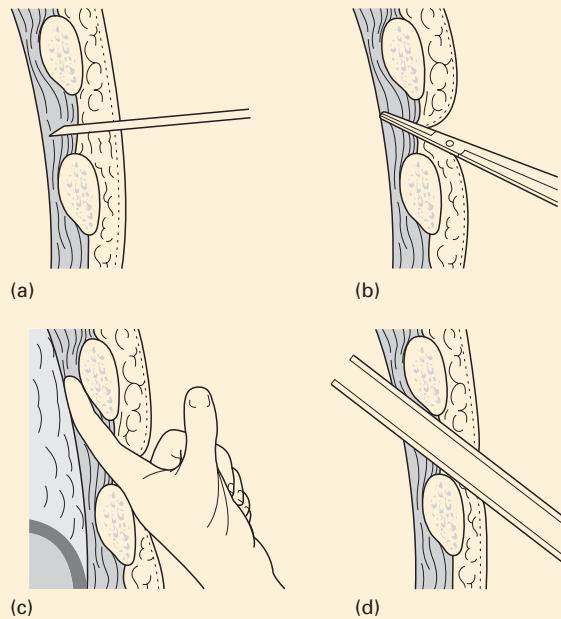


Fig. 43 Chest drain insertion. (a) Local anaesthetic is infiltrated into an intercostal space. (b) After an incision is made, blunt dissection allows access to the pleura. (c) A finger is passed through the incision to clear the lung away. (d) A chest tube is passed through the incision into the chest.

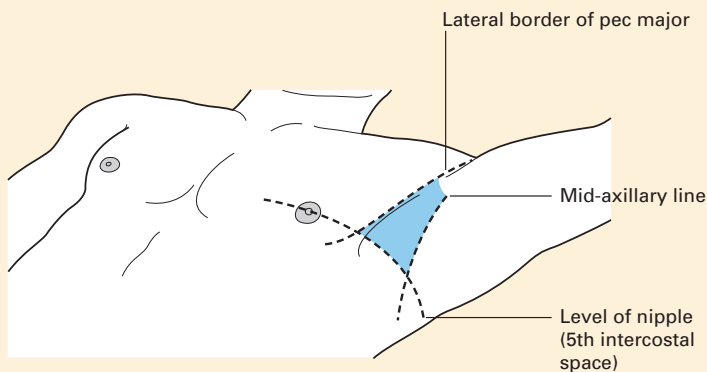


Fig. 44 Safe triangle for chest drain insertion.

Small-bore tubes (8–14F) may be inserted without blunt dissection. A needle and syringe are used to identify air/fluid and a guidewire inserted down the needle. A dilator is used to dilate the tract and a small-bore tube may be passed into the cavity under imaging guidance. Medium-sized tubes (16–24F) can be inserted using either a Seldinger technique or blunt dissection.

Larger tubes require incision and blunt dissection using a Spencer Wells forceps or similar instrument over the upper edge of a rib. In this way, the intercostal nerves and vessels that pass immediately inferior to the rib above are avoided (Fig. 45). A finger can be passed into the pleural space to ensure that no lung adhesions are in the vicinity, and then a chest tube (without a sharpened trocar if supplied) can be grasped with large forceps and passed through the incision into the pleural cavity.

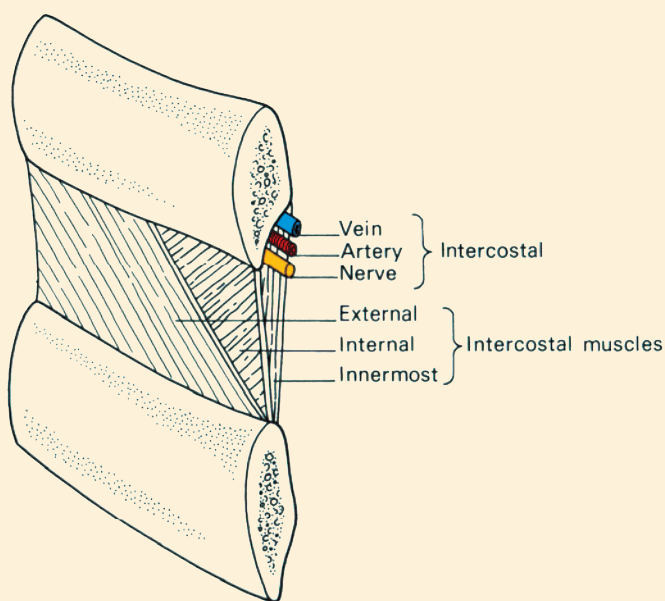


Fig. 45 The composition of an intercostal space.

The position of all chest/intrapleural catheters should be confirmed using a chest radiograph following insertion.

The intercostal spaces

The intercostal spaces are closed by thin but strong muscles and aponeuroses between which course the nerves, blood vessels and lymphatics of the chest wall (Fig. 45).

52 The respiratory pathway, lungs, thoracic wall and diaphragm

The intercostal muscles

The muscles of the intercostal spaces are disposed in three layers corresponding to the three layers of the lateral abdominal wall (Fig. 46).

The *external intercostals* pass downwards and forwards from the lower border of one rib to the upper border of the rib below, and extend from the tubercle of the rib posteriorly to the neighbourhood of the costochondral junction in front. Anteriorly, each is continued as the tough *anterior intercostal membrane* to the side of the sternum.

The *internal intercostals* extend from the sternum (or the anterior extremity of the costal cartilages in the lower spaces) to the angle of the rib posteriorly; thence, each is replaced by the *posterior intercostal membrane*. The muscle fibres run obliquely downwards and backwards.

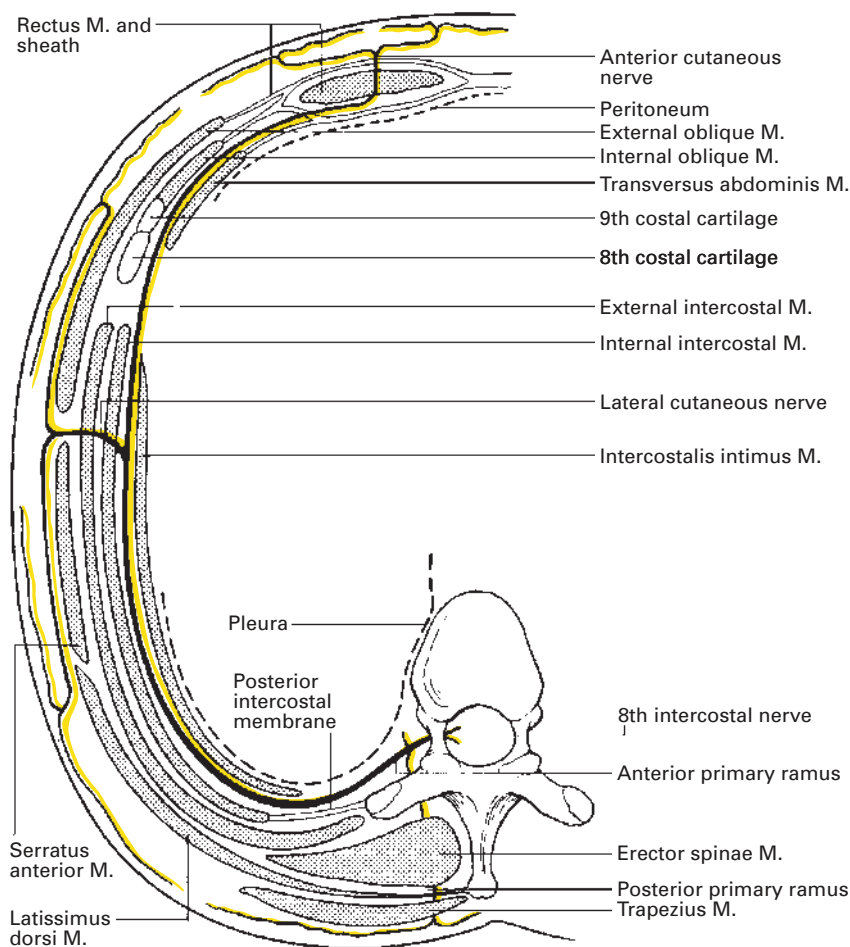


Fig. 46 Section of the distribution of the 8th intercostal nerve to show its relationships in both its thoracic and abdominal course to the muscle layers of the body wall.

The intercostal spaces 53

The *innermost layer* of muscles is incomplete and comprises the following:

- 1 *Transversus thoracis* (*sternocostalis*) anteriorly, which fans out from the side of the lower sternum to the costal cartilages of the 2nd to 6th ribs.
- 2 The *intracostals* (*intercostales intimi*) laterally, which blend with the internal intercostals except where separated by the neurovascular bundle.
- 3 The *subcostals* posteriorly, made up of small slips near the angles of the lower ribs. They run in the same direction as the internal intercostals but span two or three interspaces.

These muscle slips of the internal layer are linked to each other by membranous tissue that is continuous superiorly with the suprapleural membrane (Sibson's fascia).

The *endothoracic fascia*, equivalent to the transversalis fascia of the abdominal wall, is no more than a fine layer of areolar connective tissue between the muscles of the intercostal spaces and the parietal pleura. This allows the surgeon to strip the parietal pleura from the chest wall with ease.

The intercostal muscles in respiration

Paralysis of the intercostal muscles is known to decrease the amplitude of rib movements during quiet respiration, but the exact role of the intercostal muscles has, however, been the subject of much controversy; animal experiments, models and geometry have been invoked in attempts to solve this problem. Electromyography has greatly helped to elucidate the action of these muscles. During *inspiration*, the intercostals contract and their electrical activity increases with greater respiratory effort. During this phase there is elevation and eversion of the ribs with increase in the anteroposterior and lateral diameters of the thorax. The intercostal muscles of the lower rib spaces also contract during forcible *expiration*. In this phase, the muscles probably act from their insertions; the lower ribs are fixed by contraction of the abdominal muscles and the intercostal muscles of the lower spaces then draw down the ribs and help to diminish the thoracic volume. In addition, the intercostal muscles by their contraction maintain the rigidity of the rib spaces during violent expiration. Rigid fixation of the chest wall, for example in ankylosing spondylitis, reduces the maximum breathing capacity of the patient by some 20–30%.

The neurovascular bundle

In each intercostal space lies a neurovascular bundle comprising, from above downwards, the posterior intercostal vein, the posterior intercostal artery and the intercostal nerve, protected by the costal groove of the upper rib (Fig. 45). Posteriorly, this bundle lies between the pleura and the posterior intercostal membrane, but at the angle of the rib it passes between the internal intercostal and the intracostal muscles.

54 The respiratory pathway, lungs, thoracic wall and diaphragm

The blood vessels of the chest wall

The *posterior intercostal arteries* of spaces 3–11 arise directly from the thoracic aorta. Those of the 1st and 2nd spaces are derived from the superior intercostal artery, a branch of the costo-cervical trunk, which arches over Sibson's fascia and crosses the front of the neck of the 1st rib. In this position, the sympathetic trunk is medial and the 1st thoracic nerve root is lateral to the artery.

Each posterior intercostal artery gives off a collateral branch, and these two vessels anastomose with the two anterior intercostal arteries (see below) in the upper nine spaces.

The *posterior intercostal veins*, lying above their corresponding arteries, have a somewhat complex and variable termination.

The vein of the 1st space on each side drains into either the vertebral or the brachiocephalic vein. The 2nd, 3rd and sometimes the 4th vein join to form the *superior intercostal vein*. On the right, this enters the azygos vein; on the left, it runs across the arch of the aorta, here passing between the phrenic and vagus nerves, to terminate in the left brachiocephalic vein. The lowest eight veins empty on the right into the azygos vein and on the left into the superior and inferior hemiazygos veins (four into each).

The *internal thoracic artery* arises from the first part of the subclavian artery, descends behind the upper six costal cartilages a finger's breadth from the lateral border of the sternum, and terminates by dividing into the superior epigastric and the musculophrenic arteries. At first, the artery lies directly against the pleura but then, at the 3rd costal cartilage, it passes in front of transversus thoracis, which protects it until its termination.

Perforating branches pierce each intercostal space to supply overlying pectoralis major, skin and, in the female, breast (the 2nd to 4th being the largest vessels to this gland). Other vessels supply the mediastinum and pericardium and one accompanies the phrenic nerve (the pericardiophrenic artery). In each of the upper nine intercostal spaces, two anterior intercostal arteries are given off that anastomose with the posterior intercostal artery and its collateral branch; the first six of these branches derive from the internal thoracic artery, those to the 7th to 9th spaces arise from its musculophrenic branch.

The *internal thoracic vein* accompanies the artery and drains into the corresponding brachiocephalic vein.

Lymphatics

Lymph nodes lie alongside the internal thoracic vessels; these are important because they receive lymph from the breast which is discharged thence into the thoracic duct or mediastinal lymph trunk.

Nerves of the chest wall

The *intercostal nerves* are the anterior primary rami of T1–11; each lies in the neurovascular bundle already described. The lower five nerves (T7–11)

The intercostal spaces 55

continue onwards to supply the abdominal wall, as described elsewhere (page 319), where they maintain their anatomical position between the 2nd and 3rd layers of muscle of the body wall, i.e. between internal oblique and transversus abdominis (Fig. 46). These nerves form the segmental sensory nerve supply to the trunk and medial side of the upper arm, and the motor supply to the intercostal and anterior abdominal wall muscles.

The 1st intercostal nerve is atypical; it is the largest of the thoracic rami because of its branch which crosses the neck of the 1st rib to join C8 in the formation of the lowest trunk of the brachial plexus. Its intercostal branch is small and is entirely motor.

Each of the remaining intercostal nerves has the following branches.

- 1 *Collateral*, which arises at the angle of the rib and ends either in supplying muscle or as a connecting loop with the main nerve; it is entirely motor.
- 2 *Lateral cutaneous*, which arises in the mid-axillary line and gives off an anterior and posterior branch.
- 3 *Anterior cutaneous*, which, in each of the upper six intercostal spaces, passes in front of the internal thoracic vessels, then surfaces to supply the overlying skin. The lower five nerves pierce rectus abdominis to supply the anterior abdominal wall (Fig. 47).

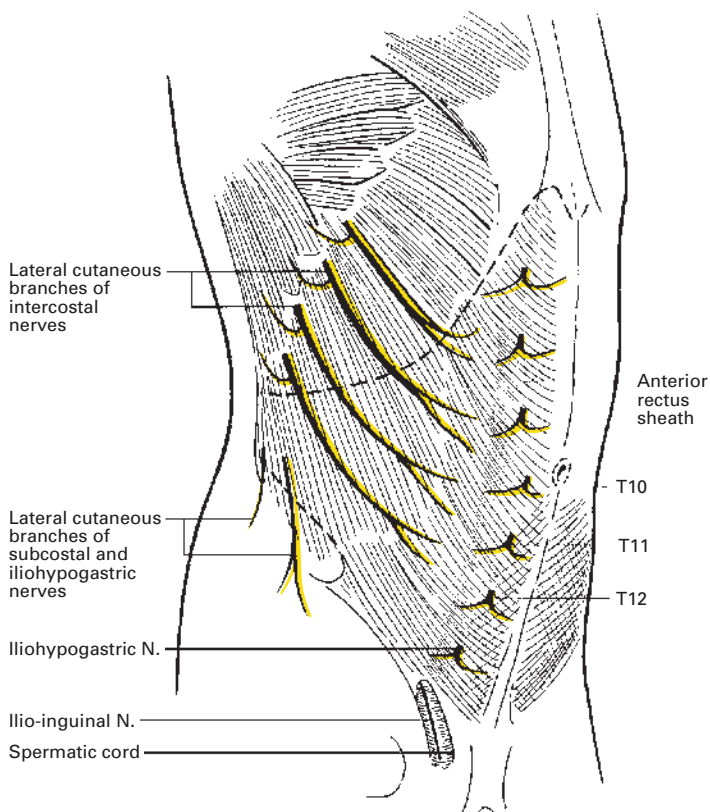


Fig. 47 View of the abdominal wall after removing the skin and superficial fascia. The lateral cutaneous and anterior cutaneous terminal branches of the nerves of the abdominal wall are demonstrated.

56 The respiratory pathway, lungs, thoracic wall and diaphragm

The lateral cutaneous branch of the 2nd intercostal is atypical; it forms the *intercostobrachial* nerve that arches over the roof of the axilla to supply the skin of the medial aspect of the upper arm as far as the elbow. As it is not part of the brachial plexus, it is not affected by brachial plexus blocks, a point of importance when an upper arm tourniquet is used on the awake patient. Local anaesthetic needs to be deposited subcutaneously at the axilla along the medial border of the upper arm in order to provide analgesia for the tourniquet.

CLINICAL NOTE

Intercostal nerve block (Fig. 48)

Intercostal nerve blocks can be used for postoperative analgesia after thoracic or upper abdominal surgery or to treat the pain of fractured ribs. They may also be used in chronic pain conditions such as post-herpetic neuralgia. The blocks should be performed at approximately the angle of the rib, with the patient in the sitting, lateral or prone position. After subcutaneous infiltration with local anaesthetic, the lower border of a rib is palpated and the palpating finger moves the skin slightly cephalad. A short hypodermic needle is inserted onto the rib towards its lower border. The needle is then 'walked' off the lower edge of the rib, and then it is advanced 3–5 mm in a slightly cephalad direction. After careful aspiration to exclude intravascular placement, 3–5 ml of local anaesthetic is injected. Care must be exercised with regard to the total dose of local anaesthetic drug injected, as multiple injections are often needed and absorption of the local anaesthetic into the circulation from this site is rapid.

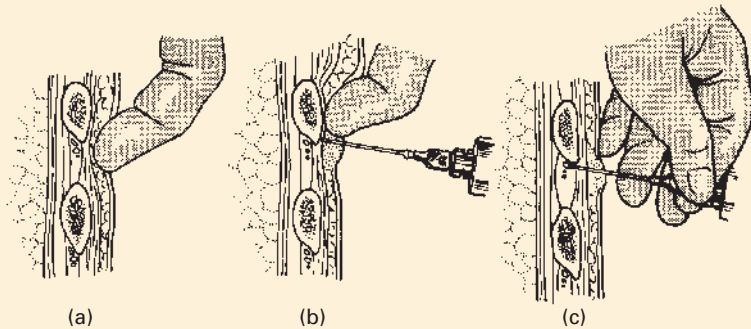


Fig. 48 Technique of intercostal blocks.

The mediastinum

The mediastinum is the region between the two pleural sacs. It is divided by the pericardium, somewhat artificially, into four compartments, which

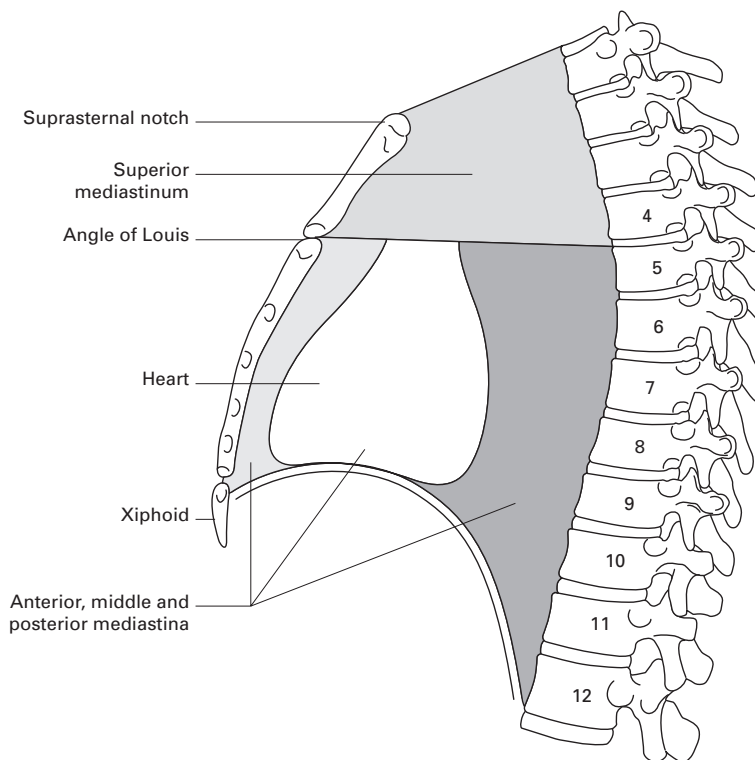


Fig. 49 The subdivisions of the mediastinum.

are, however, useful for descriptive purposes (Fig. 49): the *middle mediastinum* is the space occupied by the pericardium and its contents; the *anterior mediastinum* lies between this and the sternum; the *posterior mediastinum* lies behind the pericardium above and the diaphragm below; and the *superior mediastinum* is situated between the pericardium and the thoracic inlet.

The lungs

The shape of the lungs is a reflection of the shape of the pleural cavity on either side, very much as a jelly is a reflection of the shape of its mould. Each lung is roughly conical, with an apex, a base, a lateral (or costal) and a medial surface and with three borders – anterior, posterior and inferior (Figs 50, 51). Each lung lies freely within its pleural cavity apart from its attachments at the hilum. The right lung is the larger, weighing on average 620 g compared with 570 g on the left. The lung of the male is larger and heavier than that of the female.

The *apex* of the lung extends upwards into the root of the neck, its summit reaching 4 cm above the medial third of the clavicle. At this site, the pleura are in danger of puncture when a supraclavicular brachial plexus

58 The respiratory pathway, lungs, thoracic wall and diaphragm

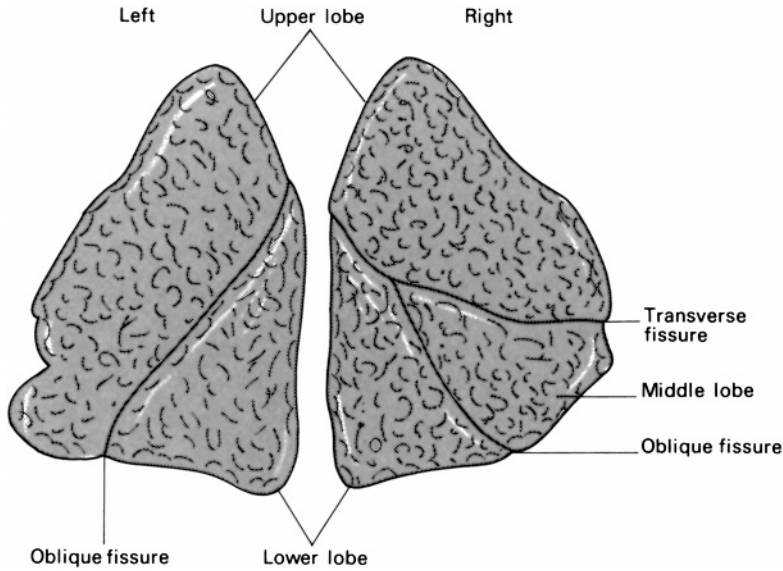


Fig. 50 The right and left lungs, posterolateral aspects.

block is performed, in subclavian vein puncture and in stab wounds of the neck. Because of the obliquity of the thoracic inlet (Fig. 49), the apex does not rise posteriorly above the neck of the 1st rib. The apex is grooved by the subclavian artery from which it is separated by cervical pleura and by the extrapleural (Sibson's) fascia.

The concave *base* of the lung rests on the dome of the diaphragm; since the right diaphragm is higher than the left, the right lung, although larger, is squatter than the left. The costal surface relates to the ribcage, which

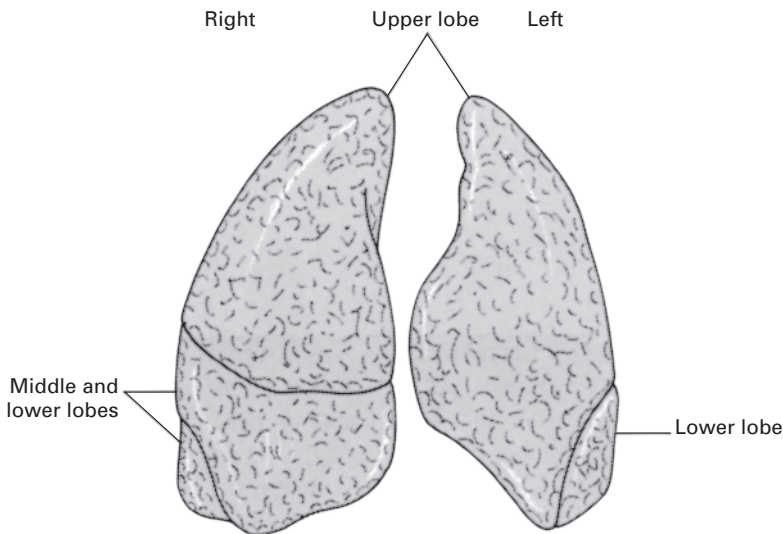


Fig. 51 The right and left lungs, anterior aspects.

The lungs 59

produces the grooving seen on the formalin-hardened lung of the dissecting-room cadaver.

The medial surface has the *hilum* as its most striking feature (see page 62). It is also related to the structures within the mediastinum, the more prominent of which produce impressions on the hardened lung; this surface may be divided into a posterior (or vertebral) part, which is in contact with the thoracic vertebral column, and an anterior (or mediastinal) portion. This is deeply concave immediately below and in front of the lung hilum, forming the cardiac impression of the heart – naturally this impression is deeper on the left than on the right (Figs 52, 53).

The medial relationships of the two lungs are different. On the right mediastinal surface (Fig. 54), the cardiac impression is formed by the right atrium and part of the right ventricle. In addition, this surface is in contact with the superior and inferior venae cavae, the vena azygos (as this arches over the hilum), the right margin of the oesophagus, the trachea, the right vagus and phrenic nerves.

The left mediastinal surface is related to the left auricle and ventricle, the aortic arch and the descending aorta, the left subclavian and common carotid arteries, left brachiocephalic vein, trachea and oesophagus, the left vagus and the thoracic duct (Fig. 55).

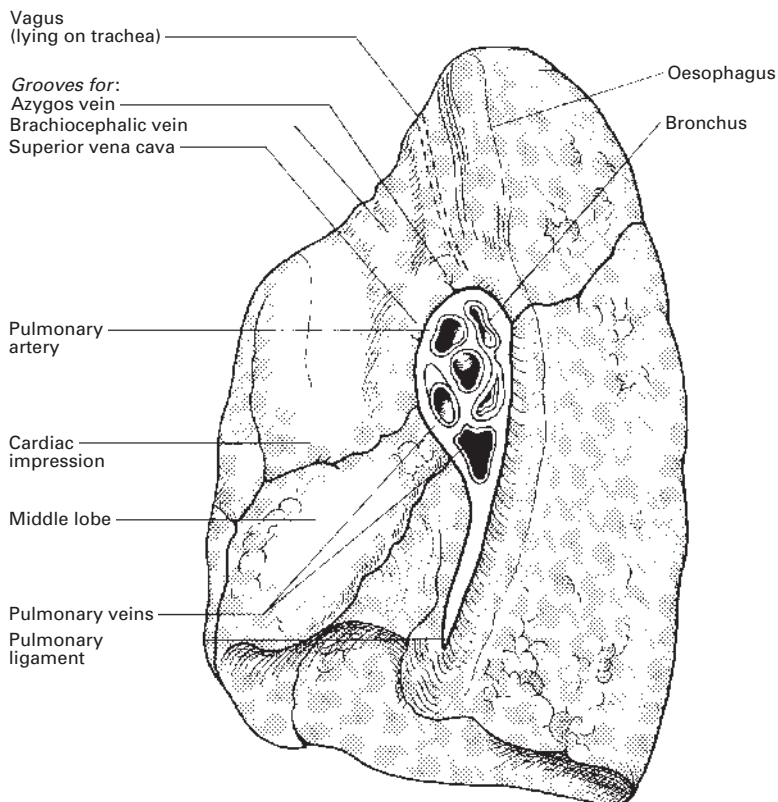


Fig. 52 The mediastinal aspect of the right lung.

60 The respiratory pathway, lungs, thoracic wall and diaphragm

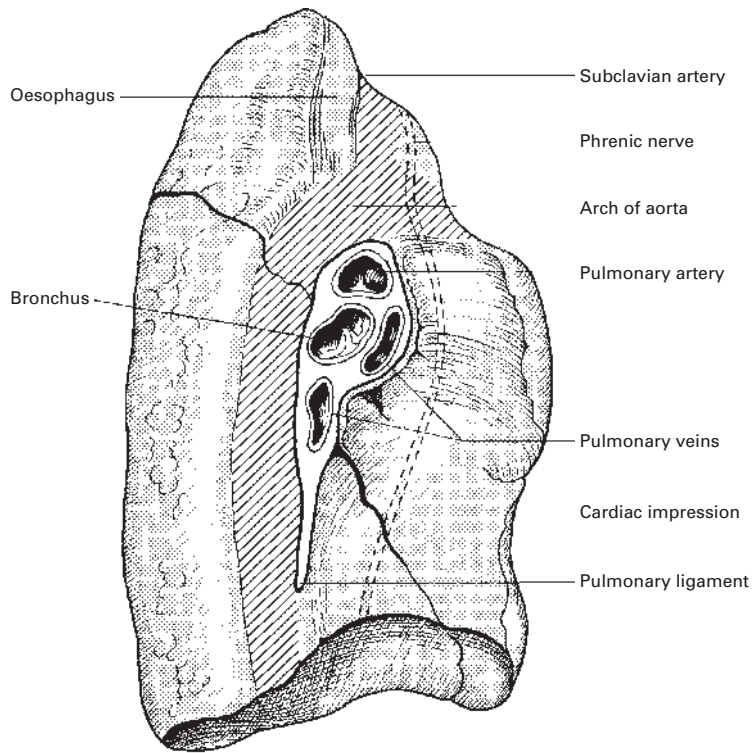


Fig. 53 The mediastinal aspect of the left lung.

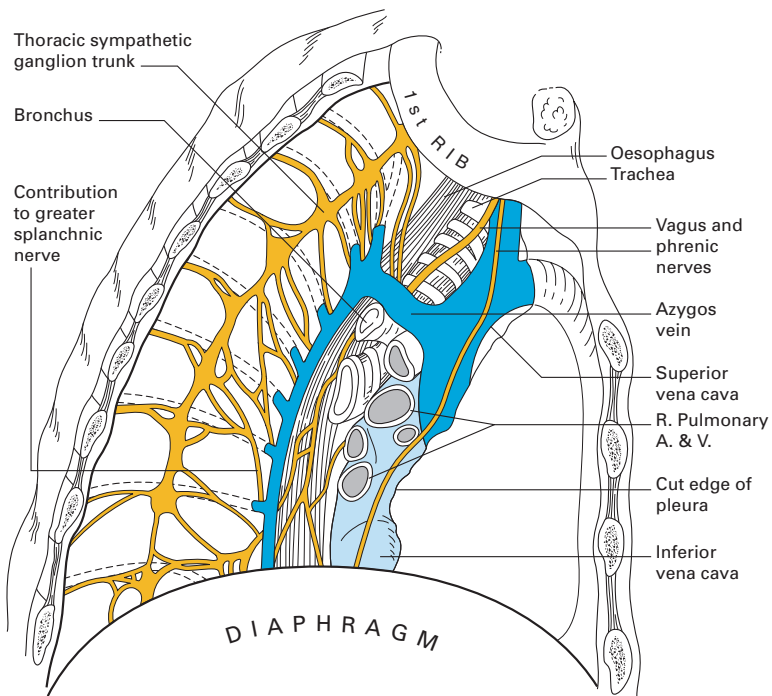


Fig. 54 The right mediastinum: the medial relationships of the right lung.

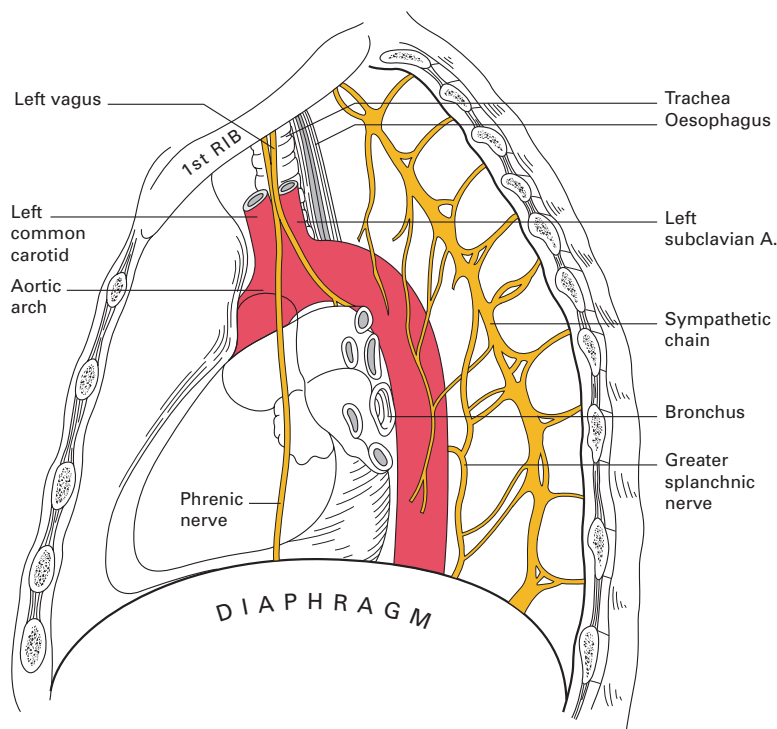


Fig. 55 The left mediastinum: the medial relationships of the left lung.

The anterior borders of the lungs are thin and insinuate themselves between the pericardium and the chest wall. On the left side, this border bears a prominent *cardiac notch*; this leaves an area of right ventricle to come into contact with the chest wall, the pericardium only intervening.

The *surface projection* of the lung is somewhat less extensive than that of the parietal pleura (Figs 41, 42) and, in addition, it varies quite considerably with the phase of respiration. The apex of the lung closely follows the line of the cervical pleura, and the surface marking of the anterior border of the right lung corresponds to that of the right mediastinal pleura. However, on the left side, the anterior border has a distinct notch (the cardiac notch) that passes behind the 5th and 6th costal cartilages. The lower border of the lung has an excursion of as much as 5–8 cm in the extremes of respiration, but, in the neutral position (midway between inspiration and expiration), it lies along a line which crosses the 6th rib in the mid-clavicular line, and the 8th rib in the mid-axillary line, and which reaches the 10th rib adjacent to the vertebral column posteriorly.

The lung lobes (Figs 50, 51)

Each lung is divided by a deep *oblique fissure*, and the right lung is further divided by a *transverse fissure*. Thus, the right lung is tri-lobed, the left bi-lobed. The right oblique fissure leaves the vertebral column posteriorly at the level of the 5th rib. It follows the rough direction of the 5th rib, tending

62 The respiratory pathway, lungs, thoracic wall and diaphragm

to lie slightly lower than this landmark, and ends near the costochondral junction either in the 5th space or at the level of the 6th rib. The left oblique fissure has a more variable origin, anywhere from the 3rd to 5th rib level, but its subsequent course is similar to that of the right side. When the arm is held above the head, the vertebral border of the scapula corresponds to the line of the oblique fissure – a useful and quite accurate surface marking.

The transverse fissure can be indicated by a horizontal line that runs from the 4th right costal cartilage to reach the oblique fissure in the mid-axillary line at the level of the 5th rib or interspace. These fissures are far from constant. More often than not, the transverse fissure is absent or incomplete. Often, the oblique fissure is partly fused in its upper part so that the superior segment of the lower lobe is fused with the adjacent upper lobe. Sometimes, in contrast, the individual bronchopulmonary segments (see page 63) are marked by indentations on the outer aspect of the lung that are occasionally deep enough to produce actual anomalous fissures. The upper limit of the lingula, for example, is often marked by an indentation on the anterior margin of the left upper lobe; this occasionally extends so deeply that there appears to be a left middle lobe. The apex of the right lung may be cleft by the arch of the azygos vein which, complete with its 'mesentery' of pleura, divides off a medially placed *azygos lobe* or lobule. This may be large and almost completely isolated, or may be merely a slight indentation of the upper lobe by the azygos vein.

The relationships at the root of the lung

(Figs 52, 53)

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, lymphatics, lymph nodes and autonomic nerves. Each of these constituents is considered elsewhere, but here we must discuss their hilar relationships. These are more readily remembered logically than learned by rote.

The bronchi lie in a plane behind the heart and the roots of the great vessels – therefore the bronchus will be situated posteriorly to the pulmonary vessels. The pulmonary arteries lie along the upper borders of the atria; the pulmonary veins drain, two on each side, into the left atrium – therefore the artery must lie above the veins. The bronchial vessels hug the posterior surface of the bronchi, and this is the relationship they adopt at the hilum. Finally, the whole complex is sandwiched between the anterior and posterior pulmonary nerve plexuses.

There remains but one fact to remember: on the right side there is an additional upper lobe bronchus at the hilum which lies above ('eparterial'), but still posterior to, the pulmonary vessels.

The relationships of the lung roots themselves may be summarized thus:

- 1 on the left: in front, the phrenic nerve; behind, the descending aorta and the vagus nerve; above, the aortic arch; below, the pulmonary ligament;

2 on the right: in front, the superior vena cava and the phrenic nerve; behind, the vagus nerve; above, the vena azygos; below, the pulmonary ligament.

The bronchopulmonary segments

(Figs 56–58)

The concept of the anatomy of the lung has been revolutionized by the recognition that the lung is divided, functionally, not into the lobes described above, but into a series of bronchopulmonary segments each with its own bronchus, its own blood supply from the pulmonary artery and with its parenchyma distinct from adjacent segments. Lung resection surgery, postural drainage and chest radiodiagnosis are largely based on the detailed anatomy of these segments.

The arrangement of the bronchopulmonary segments varies somewhat in the two lungs but, were it not that the lingular branches arise from the upper lobe bronchus on the left, and the middle lobe branches derive from the lower part of the main bronchus on the right, the basic pattern would be essentially the same.

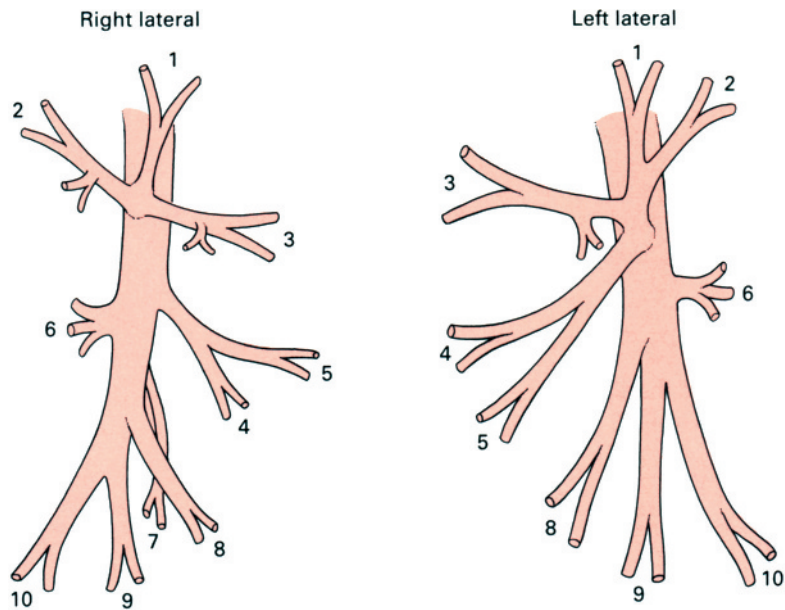
In the following description, the numbers in parentheses correspond with those used in Figs 56–58.

The right lung

The right main bronchus, after a course of some 2.5 cm, gives off at right angles the *upper lobe bronchus*. After a 1 cm course, this in turn trifurcates or else has a very close double bifurcation into three segmental bronchi: the *apical* (1), which passes upwards and laterally; the *posterior* (2), which passes backwards, laterally and slightly upwards; and the *anterior* (3), which passes forwards, slightly laterally and slightly downwards. The main bronchus then continues as a long (3 cm) length of primary bronchus before giving off a forward and downward directed branch that is the *middle lobe bronchus*. This is 1–1.5 cm long, and bifurcates into the lateral (4) and medial (5) divisions of the middle lobe.

The long segment of bronchus between the upper lobe bronchus and the middle lobe bronchus has not yet acquired a definitive name; it is best referred to simply as the 'lower part of the right main bronchus'. It is this portion that is crossed by the main trunk of the right pulmonary artery, hence the old term 'hyparterial bronchus' – in contrast to the right upper lobe bronchus, which is above the artery and which was termed, in older anatomical works, the 'eparterial bronchus'.

Opposite and just below the origin of the middle lobe bronchus (or occasionally on a level with it) arises the bronchus to the *apical segment of the lower lobe* (6). This bronchus passes directly backwards as a short trunk, up to 1 cm long, which then trifurcates into superior, medial and lateral branches. When a patient lies in bed, this bronchus projects directly posteriorly from the stem of the lower lobe bronchus and is therefore frequently the place in which an inhaled body or retained secretions tend to collect.

64 The respiratory pathway, lungs, thoracic wall and diaphragm**Right***Upper lobe*

- 1 Apical bronchus
- 2 Posterior bronchus
- 3 Anterior bronchus

Middle lobe

- 4 Lateral bronchus
- 5 Medial bronchus

Lower lobe

- 6 Apical bronchus
- 7 Medial basal (cardiac) bronchus
- 8 Anterior basal bronchus
- 9 Lateral basal bronchus
- 10 Posterior basal bronchus

Left*Upper lobe*

- 1 } Apicoposterior bronchus
- 2 } Apicoposterior bronchus
- 3 Anterior bronchus

Lingula

- 4 Superior bronchus
- 5 Inferior bronchus

Lower lobe

- 6 Apical bronchus
- 8 Anterior basal bronchus
- 9 Lateral basal bronchus
- 10 Posterior basal bronchus

Fig. 56 Diagram of the branches of the bronchial tree.

About 1.5 cm below the superior (apical) bronchus of the lower lobe is given off the *medial basal (or cardiac) bronchus* (7), which originates from the medial side of the main stem of the lower lobe bronchus. Then, in rapid succession, are given off the other basal bronchi:

- 1 the *anterior basal* (8), which runs downwards, forwards and laterally;
- 2 the *lateral basal* (9), which runs downwards and laterally; and
- 3 the *posterior basal* (10), the largest branch, which runs downwards and backwards, continuing the direction of the main lower lobe bronchus.

Fig. 57 The segments of the right lung. The key of the numbering is given in Fig. 56.

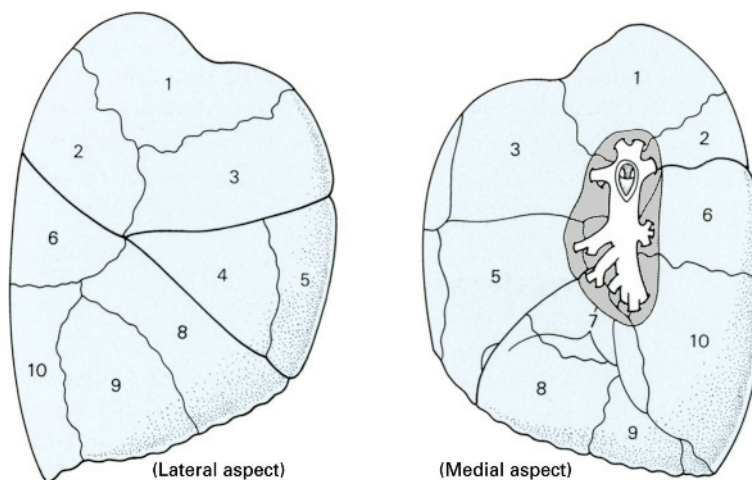
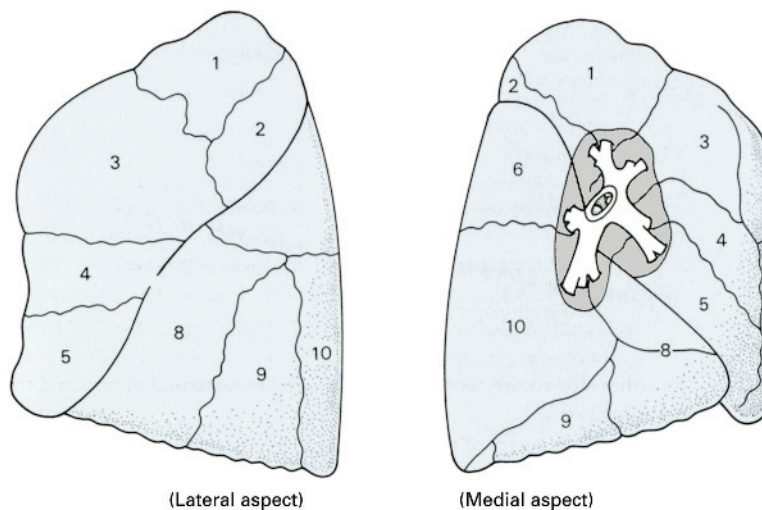


Fig. 58 The segments of the left lung. The key of the numbering is given in Fig. 56.



The left lung

The left main bronchus has a course of 5 cm before giving off the left upper lobe bronchus. The left pulmonary artery loops above this bronchus and there is thus no 'eparterial bronchus' comparable to that of the right side. The *upper lobe bronchus* passes laterally for about 1 cm, and then bifurcates into a *superior* and an *inferior (or lingular) division*. The superior division soon divides to supply the *apical, anterior* and *posterior* segments of the upper lobe just as on the right side, except that usually the apical and posterior bronchi originate by a common trunk, termed the *apico-posterior bronchus* (1 and 2), shortly after the separate anterior bronchus (3) is given off. Sometimes, the three bronchi arise independently, as on the right side.

The inferior division of the left upper lobe bronchus supplies the *lingula*, the tongue-like projection that constitutes the antero-inferior part

66 The respiratory pathway, lungs, thoracic wall and diaphragm

of the left upper lobe. This lingular bronchus passes downwards, forwards and somewhat laterally and then bifurcates, after 1–2 cm, into *superior* (4) and *inferior* (5) branches. This division into superior and inferior segments is quite characteristic of the lingular lobe and is in contrast to the medial and lateral divisions of the middle lobe on the right side. An indentation on the anterior margin of the upper lobe frequently marks the upper limit of the lingula (Fig. 58).

The downward direction of the lingular bronchus explains the frequency with which the lingular segment is affected, together with the left lower lobe, in infections and in bronchiectasis.

The bronchi of the left lower lobe resemble the distribution on the right side except there is no medial basal (cardiac) branch.

Bronchoscopic anatomy

The segmental anatomy of the bronchial tree must now be related to the appearance at bronchoscopy (Fig. 59).

The trachea is seen as a glistening tube, which is white at the rings of cartilage and reddish between. This tube is flattened somewhat where it is crossed by the aortic arch, the pulsations of which can be observed through the tracheal wall. The tracheal bifurcation, or carina, lies a little to the left

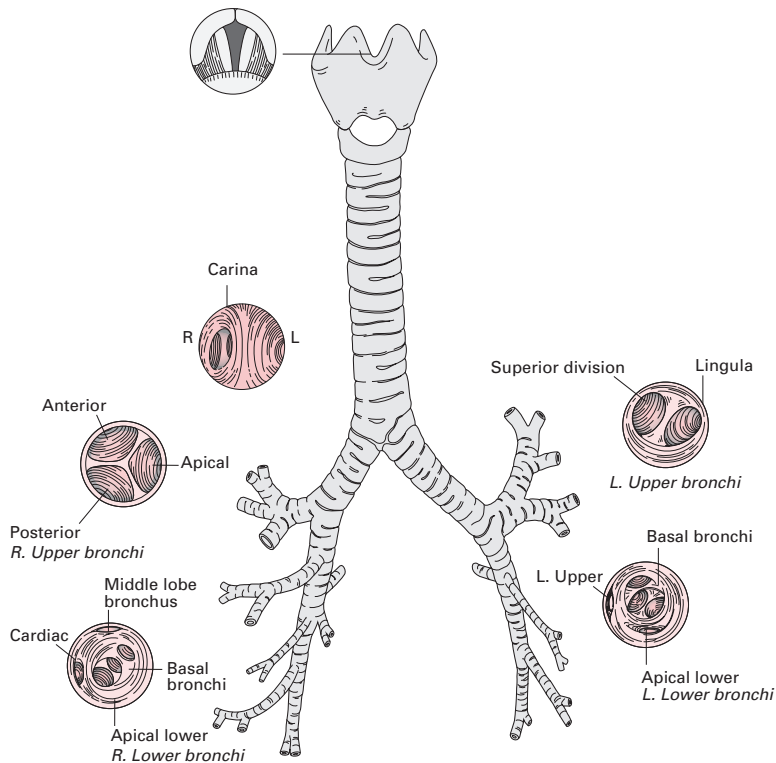


Fig. 59 The bronchoscopic anatomy of the bronchial tree.

of the mid-tracheal line, because of the more vertically situated right main bronchus; it has the appearance of a short, sharp, shining, sagittal ridge.

It is then easier to advance down the wider and more vertical right main bronchus. First, the orifice of the right upper lobe bronchus is seen on its lateral wall. Inspection of this reveals the typical division into three openings of equal size, giving a characteristic tricornate appearance. Looking into the main orifice, the orifices of its anterior, posterior and apical branches can be seen. Still advancing, a horizontal ridge appears as the anteriorly placed orifice of the middle lobe bronchus comes into view. Below this, we pass into the lower lobe bronchus. Posteriorly, its apical branch orifice can be seen, then the cardiac orifice appears on the medial side, and finally clumped close together, from above down, appear the anterior basal, lateral basal and posterior basal orifices.

Withdrawing the instrument to the trachea and now advancing it along the left main bronchus, the first feature of note is the greater length of main bronchus encountered before the orifice of the left upper lobe bronchus appears on the lateral wall. The upper lobe bronchus rapidly divides into the lingular bronchus and the left upper lobe bronchus proper. Advancing along the lower lobe bronchus brings its apical branch into view posteriorly; then, beyond this, the cluster of orifices of the anterior, lateral and posterior basal bronchi.

The structure of the lung and bronchial tree

The basic arrangement of the bronchial wall comprises mucosa, basement membrane, a submucous layer of elastic tissue, non-striated bronchial muscle and, finally, an outer fibrous coat containing cartilage.

The lining epithelium of the trachea and larger bronchi is in several layers: a basal layer, which rests on a well-defined basal membrane, an intermediate zone of spindle-shaped cells and a superficial sheet of columnar ciliated cells which are interspersed with mucus-secreting goblet cells. In chronic inflammatory conditions, the ciliated epithelium becomes replaced by stratified cells, which are non-ciliated. This metaplasia may also occur following prolonged intubation of the trachea and tracheostomy. In the finer bronchi, the epithelium becomes cuboidal and ciliated, with far fewer goblet cells. The alveoli are lined with a layer of epithelium which is so thin that, except where nuclei are present, it is often invisible in conventionally prepared histological material. Electron microscopy and special staining techniques have shown that the epithelium is, in fact, intact – although with a thickness of only 0.2 μm away from the cell nuclei – and rests on a fine basement membrane. Alveolar air is thus separated from blood in the pulmonary capillary tree by an extremely fine membrane which, nevertheless, consists of four layers: capillary wall, capillary basement membrane, alveolar basement membrane and alveolar epithelium. Among the flattened epithelial cells of the alveolar wall are others that are large and have a vacuolated appearance. These are the type II pneumocytes, which secrete surfactant – the surface-action lipoprotein complex (phospholipoprotein) that prevents the air bubbles contained in the alveoli from collapsing.

68 The respiratory pathway, lungs, thoracic wall and diaphragm

Although surfactant is present in the fetal lung at as early as 2–3 weeks, it occurs in increasing amounts until maturity. The development of surfactant can be inferred from the presence of lecithin in the amniotic fluid. Absence of surfactant because of either immaturity or genetic abnormality is responsible for the respiratory distress syndrome of the newborn.

The submucous layer of the bronchial tree consists of longitudinally disposed elastic fibres that donate the important property of elastic recoil to the air-conducting system. This layer also contains a rich capillary vascular plexus and lymphoid tissue. It is this elastic layer that produces the force of retraction, which tends to pull the lung away from the chest wall and so creates a negative intrapleural pressure. As the patient ages, the amount of elastic recoil diminishes. This results in the progressive decrease in intrapleural pressure in elderly patients and accounts for some of the decrease in pulmonary compliance and functional residual capacity.

Deep to this elastic layer is the zone of non-striated muscle. The muscle fibres of the bronchial tree form a 'geodesic network'. A geodesic line is the shortest line between two points on a surface (for example, an arc connecting two points on a sphere), and is the ideal engineering arrangement for producing or withstanding pressures within a tube, combined with least tendency for the fibres to slip along its surface. The *relative* thickness of the muscle coat increases as the branching bronchi become narrower and is in greatest proportion in the terminal bronchioles. The muscle layer forms a sphincter around the openings from the alveolar ducts that lead into the atria (see below), beyond which the muscle fibres disappear.

The cartilage rings of the extrapulmonary main bronchi are replaced in their intrapulmonary branches by irregular cartilaginous plates that are embedded in the outer fibrous coat of the bronchi. At every bronchial division, there is a saddle-shaped piece of cartilage that reinforces the two branches at their bifurcation.

The cartilages become progressively smaller and more incomplete; they finally disappear entirely in bronchioles of approximately 0.6 mm diameter.

The air spaces (Fig. 60)

The successive subdivisions of the terminal part of the bronchial tree are:

- 1 bronchioli;
- 2 respiratory bronchioli;
- 3 alveolar ducts;
- 4 atria;
- 5 air sacs (or alveolar sacs);
- 6 air cells (or alveoli).

The *bronchioles* are the finer bronchial ramifications from whose walls cartilage has disappeared; they are usually of the region of 0.6 mm in diameter. Their walls are made up largely of a comparatively thick zone of bronchial muscle and they are lined by a cuboidal ciliated epithelium with but few goblet cells. Between the epithelium and muscle is a thin elastic lamina. The *respiratory bronchioles* bear small alveoli, or air cells, on

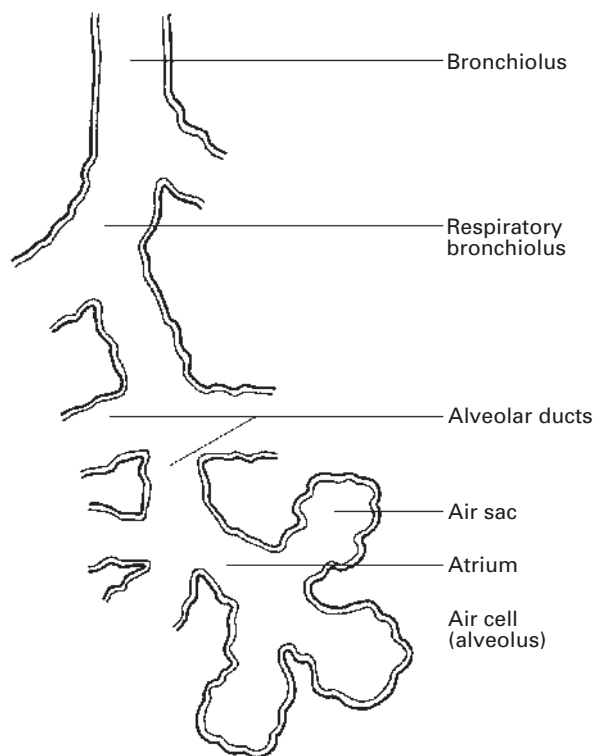


Fig. 60 The anatomy of the bronchial terminations.

their walls and are lined by a non-ciliated cuboidal epithelium. The distal extremity of each respiratory bronchiole is termed the *alveolar duct*. From three to six roughly spherical chambers arise from the termination of each alveolar duct. These are the *atria* which, in turn, give rise to a number of air sacs whose walls are studded with extremely thin-walled *air cells* or *alveoli*.

Each bronchiole with its subdivisions is termed a primary lung lobule.

The pulmonary blood supply

The pulmonary artery provides a capillary plexus in intimate relationship to the alveoli and is concerned solely with alveolar gas exchange. The blood supply to the lung itself, to its lymph nodes, to the bronchi and to the visceral pleura is entirely provided by the bronchial arteries. Venous drainage from the walls of the larger bronchi is carried out by the bronchial veins; the drainage of the smaller bronchi, together with that of the alveolar capillaries, is a function of the pulmonary veins. Thus, although there is no communication between the bronchial and pulmonary arteries, a good deal of blood brought to the lung by the bronchial arteries is drained by the pulmonary veins.

The *pulmonary artery* and its subdivisions closely follow the ramifications of the bronchial tree, so that each air sac has its own minute

70 The respiratory pathway, lungs, thoracic wall and diaphragm

twig, which then breaks up into capillaries that form the richest vascular network in the body. The *pulmonary vein* tributaries are derived partly from the capillaries of the pulmonary artery and partly from those of the bronchial artery. Unlike the branches of the pulmonary artery, which run in close relation to the bronchial tree, the venous tributaries lie between the lung segments, thus providing a valuable landmark to the surgeon in the performance of segmental resections. At the apex of each bronchopulmonary segment, the pulmonary vein draining that segment meets the segmental artery and passes alongside it to the hilum.

There are two main pulmonary veins on each side, which drain separately into the left atrium. On the left side, the upper and lower lobe each have their own main pulmonary vein; on the right side, the upper and middle lobes share the upper pulmonary vein, the lower lobe drains via the lower vein.

The *bronchial arteries* are to the lungs what the hepatic artery is to the liver: they supply the actual pulmonary stroma – the bronchi, lung tissue, visceral pleura and pulmonary nodes.

The arteries are variable in both number and origin; there are usually three, 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 artery is more variable; it may arise from the aorta, the 1st intercostal artery, the 3rd intercostal artery (which is the 1st intercostal branch of the aorta), the internal thoracic artery or the right subclavian artery. Occasionally, all three arteries arise from a common trunk derived from the aorta.

The arteries lie against the posterior walls of their respective bronchi. They follow and supply the bifurcating bronchial tree as far as the small bronchioles but disappear as soon as alveoli appear in the walls of the ducts; all available respiratory epithelium is thus supplied from the pulmonary arterial tree.

The *bronchial veins* are usually two in number on each side; the right drain into the azygos vein, the left into the superior hemiazygos or the left superior intercostal vein. They only drain blood from the first two or three bifurcations of the bronchial tree; more distally the bronchial arterial blood drains into the radicles of the pulmonary veins.

The bronchial blood flow, together with that in the *venae cordis minimae* (Thebesian veins) of the heart, constitutes a physiological shunt whereby venous blood is mixed with arterial blood in the heart. An increase in bronchial blood flow may occur during acute pulmonary infections and bronchiectasis and will inevitably increase the shunt effect. Normally, this shunt of venous blood to the left side of the heart constitutes less than 1–2% of the cardiac output; this is the so-called ‘physiological shunt’. In the normal individual, this shunt is increased by minimal ventilation/perfusion mismatching in the lung and may then total 5% of the cardiac output.

The fine arrangement of the blood vessels within the bronchial wall is of some practical interest. The arterial plexus derived from the bronchial artery lies external to the bronchial muscle; vessels pierce the muscle coat to form a capillary plexus in the submucosa. The venous radicles, in turn, pierce the muscle layer in order to drain into the venous plexus

in the areolar tissue outside the muscle. Blood must therefore traverse the bronchial muscle both to reach and to leave the submucous capillary plexus. Oedema of the bronchial wall will occlude the low-pressure veins before the high-pressure arteries; the resultant venous obstruction produces further mucosal swelling and thus accentuates the bronchial obstruction.

Lymphatics

A superficial lymphatic plexus drains the visceral pleura; a deep plexus, lying alongside the pulmonary vessels, drains the bronchi but does not reach beyond the alveolar ducts into the more distal air spaces. Both lymphatic plexuses drain into bronchopulmonary lymph nodes placed at the points of bifurcation of the larger bronchi. Thence, lymph drains to the tracheobronchial nodes, which, in turn, empty into the right and left bronchomediastinal trunks. The right trunk may drain into the right lymph duct and the left may empty into the thoracic duct. More often, they open directly and independently into the junction between the internal jugular and the subclavian veins on either side.

Innervation

Sympathetic (T2–4) and parasympathetic (vagal) fibres form a posterior pulmonary plexus at the root of the lung. Fibres pass thence around the lung root to form an anterior pulmonary nerve plexus. Fibres stream from these plexuses into the lung along the blood vessels and bronchi.

The mucous glands are supplied by secretomotor parasympathetic fibres. The bronchial muscles receive bronchodilator (inhibitory) fibres from the sympathetic system and bronchoconstrictor fibres from the vagus. The bronchial vessels are under sympathetic vasomotor control, which is much less in evidence in the case of the thin-walled pulmonary vascular bed; this is little affected by sympathetic stimulation and is mainly passively controlled, e.g. by right ventricular pressure.

Afferent fibres, sensitive to stretch, are transmitted from the lung via the vagus to the medullary respiratory centre.

The development of the respiratory tract

In the early fetus (the 3 mm embryo), a median ventral diverticulum appears in the foregut, which is termed the tracheobronchial groove. This gradually deepens and its edges nip together caudally so that the diverticulum becomes separated from the primitive oesophagus except at the laryngeal aditus. Meantime, the caudal prolongation of the diverticulum divides into the two main bronchi and further proliferation results in the formation of the lung bud on each side. A persistent tracheo-oesophageal fistula may occur as an embryonic anomaly, which indicates the close developmental relationship between the foregut and the respiratory

72 The respiratory pathway, lungs, thoracic wall and diaphragm

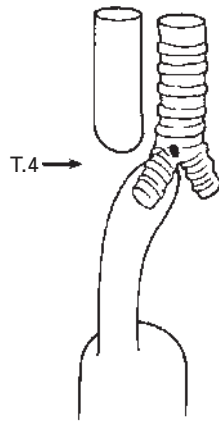


Fig. 61 The usual anatomy of a congenital tracheo-oesophageal fistula: the upper oesophagus ends blindly; the lower oesophagus is connected with the trachea at the level of the 4th thoracic vertebra.

passages; it is usually associated with atresia of the oesophagus, the fistula being situated below the atretic segment (Fig. 61).

The diaphragm

The diaphragm constitutes the great muscular septum between the thorax and the abdomen; it is one of the distinguishing features of mammalian anatomy.

Anatomical features (Fig. 62)

The diaphragm consists of peripheral muscle with a central trefoil-shaped tendon of strong interlacing bundles that blend above with the fibrous pericardium. The muscle takes a complex origin from the crura, the arcuate ligaments, the costal margin and the xiphoid.

The *crura* arise from the lumbar vertebral bodies; the left from the 1st and 2nd, the larger right from the 1st, 2nd and 3rd.

The *arcuate ligaments* are the *median*, which is a fibrous arch joining the two crura, the *medial*, which is a thickening of the fascia over the psoas, and the *lateral*, which is a condensation of fascia over quadratus lumborum ending laterally near the tip of the 12th rib.

The *costal origin* is from the tips of the last six costal cartilages.

The *xiphoid origin* comprises two slips from the posterior aspect of the xiphoid.

The diaphragmatic foramina (Figs 62, 63)

The three major openings are for:

- 1 the inferior vena cava, at the level of the body of the 8th thoracic vertebra;

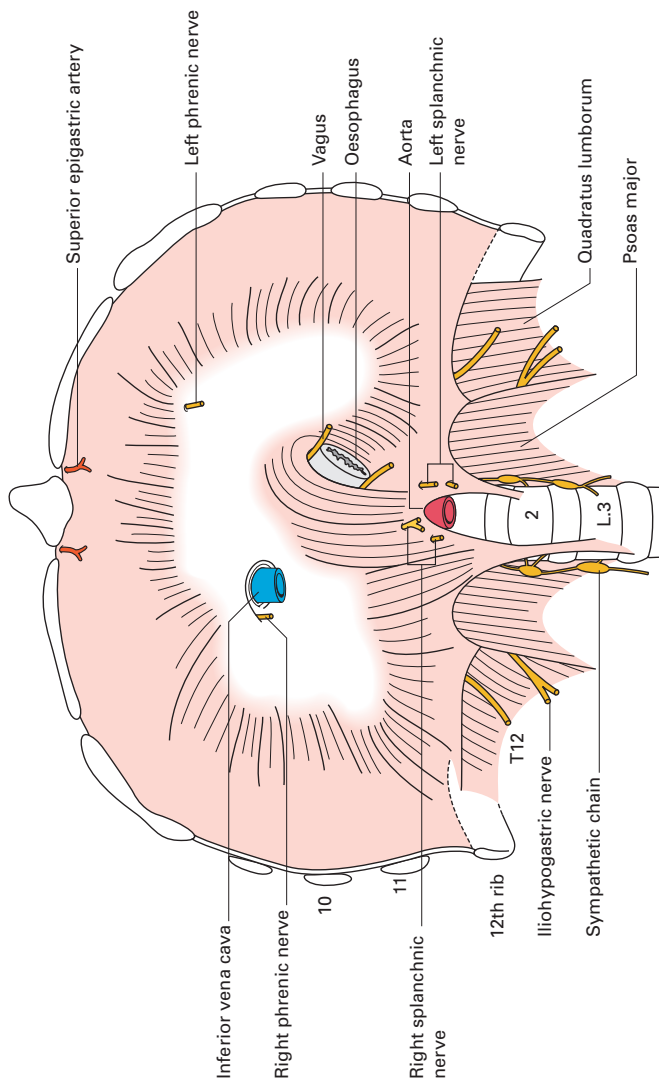


Fig. 62 The abdominal aspect of the diaphragm.

74 The respiratory pathway, lungs, thoracic wall and diaphragm

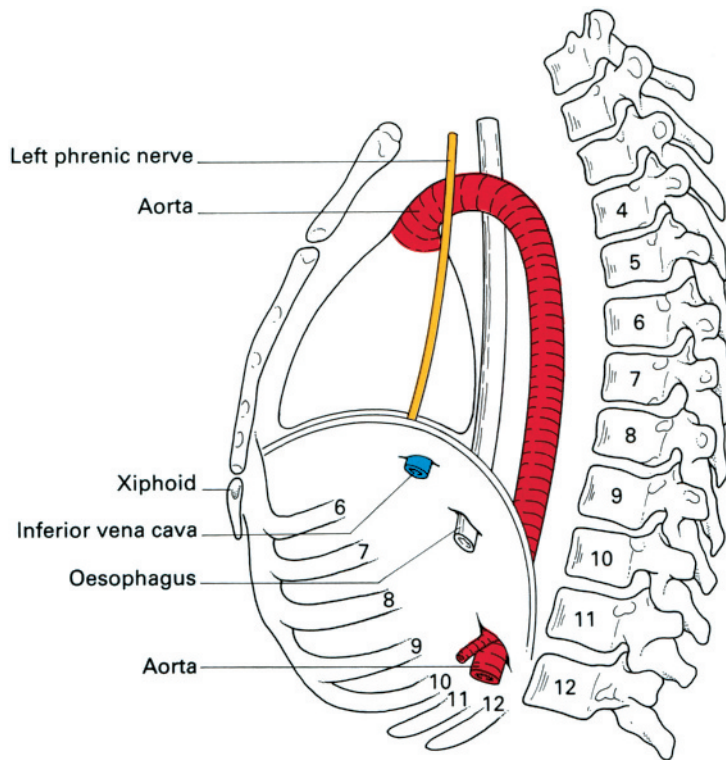


Fig. 63 Lateral view of the diaphragm to show the levels at which it is pierced by major structures.

- 2 the oesophagus, together with the vagi and the oesophageal branches of the left gastric vessels, at T10;
- 3 the aorta, together with the thoracic duct and azygos vein, behind the median arcuate ligament at T12.

In addition, the sympathetic trunk passes behind the medial arcuate ligament, the splanchnic nerves pierce the crura, the hemiazygos vein drains through the left crus, the superior epigastric vessels pass between the xiphoid and costal origins of the diaphragm into the posterior rectus sheath, the lower intercostal nerves and vessels enter the anterior abdominal wall between the interdigitations of the diaphragm and transversus abdominis and lymphatics stream from the retroperitoneal tissues through the diaphragm to the mediastinum.

The oesophageal hiatus is reinforced by a sling of muscle fibres from the right crus, which probably plays a part in maintaining competence at the oesophagogastric junction. Not uncommonly, the left crus supplies some of the fibres forming this sling, which is occasionally derived solely from it.

Nerve supply

The phrenic nerve (C3–5; see page 164 for a detailed description) provides the motor supply of the diaphragm, apart from an unimportant

The diaphragm 75

contribution to the crura from T11 and T12. Section of the phrenic nerve is followed by complete atrophy of the corresponding hemidiaphragm. The phrenic nerve also transmits proprioceptive fibres from the centre of the diaphragm, although the periphery of this muscle has its sensory supply from the lower thoracic nerves.

The right phrenic nerve pierces the central tendon to the lateral side of the inferior vena cava (some fibres may actually accompany the vein through its foramen). The left nerve pierces the muscle about 1 cm lateral to the attachment of the pericardium. The terminal fibres of each nerve supply the muscle on its abdominal aspect.

The diaphragm as a muscle of respiration

The apex of the dome of the diaphragm reaches the level of the 5th rib in the mid-clavicular line, i.e. it is level with a point about 2.5 cm below the nipple. The right hemidiaphragm is rather higher than the left, and both domes rise somewhat in the horizontal position. When the subject lies on his/her side, the upper cupola sinks to a lower level than its partner and its movements are relatively diminished. The level of the diaphragm is elevated in late pregnancy, gross ascites or obesity, in pneumoperitoneum and in patients with large abdominal tumours; such subjects all have some degree of respiratory limitation.

In inspiration, the diaphragm moves vertically downwards (the domes considerably more than the central tendon), and this has a piston-like action in enlarging the thoracic cavity. A subsidiary effect is that the lower costal margin is raised and everted with consequent expansion of the base of the thorax.

In expiration, the diaphragm relaxes; in forced expiration, it is actually pushed upwards by the increased intra-abdominal pressure effected by contraction of the muscles of the anterior abdominal wall.

It is estimated that the movement of the diaphragm accounts for some 60–75% of the total tidal volume of respiration; in some subjects during quiet breathing, it may, indeed, be the only functioning muscle in inspiration. It is therefore interesting that bilateral phrenic interruption with complete diaphragmatic paralysis may cause little respiratory difficulty, providing the lungs are relatively normal. In quiet respiration, the diaphragm has a range of movement of 1.5 cm. In deep breathing this increases to 7–13 cm.

In addition to its important role as a muscle of respiration, the diaphragm helps increase the intra-abdominal pressure in defecation, micturition, vomiting and parturition, as well as taking part in the mechanism of the 'cardiac sphincter' (see below).

The diaphragm and the 'cardiac sphincter'

At the cardio-oesophageal junction, there exists a rather extraordinary sphincter mechanism that allows food and liquids to pass readily into the stomach, which prevents free regurgitation into the oesophagus even

76 The respiratory pathway, lungs, thoracic wall and diaphragm

when standing on one's head or in forced inspiration (when there is a pressure difference of approximately 80 mmHg between the intragastric and intra-oesophageal pressures), but which can relax readily to allow vomiting or belching to occur.

In spite of extensive investigations, the exact nature of this sphincter is not understood. It is probably a complex affair made up of:

- 1 a physiological muscular sphincter at the lower end of the oesophagus;
- 2 a plug-like action of the mucosal folds at the cardia;
- 3 a valve-like effect of the obliquity of the oesophagogastric angle;
- 4 a diaphragmatic sling that maintains the normal position of the cardia and has a pinch-cock action on the lower oesophagus;
- 5 the positive intra-abdominal pressure that tends to squeeze the walls of the intra-abdominal portion of the oesophagus together.

Although a true anatomical sphincter cannot be shown by dissection, a physiological sphincter can be deduced from the high-pressure zone demonstrated within the lower oesophagus, which disappears when the oesophageal muscle is divided, as in Heller's operation for achalasia of the cardia. Reinforcing the sphincter are the mucosal folds of the cardia, which act as a plug wedged within the muscular ring.

The crural sling of the diaphragm around the lower oesophagus is important in maintaining the normal position of the cardio-oesophageal junction below the diaphragm. If the hiatus is enlarged and lax, the stomach can slide upwards into the chest (a 'sliding hiatus hernia') and the normal valve-like angle between oesophagus and cardia straightens out.

There also appears to be a definite pinch-cock mechanism on the oesophagus when the diaphragm contracts in full inspiration – a phase at which intrathoracic pressure is lowest, intra-abdominal pressure highest and conditions most favourable for fluids to be forced at high pressure upwards through the cardiac orifice. The diaphragm is an important but not essential part of the cardiac sphincter mechanism, since a sliding hiatus hernia is not necessarily accompanied by regurgitation providing the physiological sphincter is competent. Similarly, free regurgitation occurs in some subjects with an apparently normal oesophageal hiatus, presumably because of some defect in the function of the physiological sphincter.

The development of the diaphragm

The diaphragm is formed (Fig. 64) by fusion in the fetus of:

- 1 the septum transversum, which constitutes the central tendon;
- 2 the dorsal oesophageal mesentery;
- 3 a peripheral rim derived from the body wall;
- 4 the pleuroperitoneal membranes, which close the primitive communications between the pleural and peritoneal cavities.

The septum transversum is the mesoderm which, in early development, lies in front of the head end of the embryo. With the folding off of the head, this mesodermal mass is carried ventrally and caudally, to lie in its definitive position at the anterior part of the diaphragm. During this migration, the cervical myotomes and nerves contribute muscle and nerve supply,

The diaphragm 77

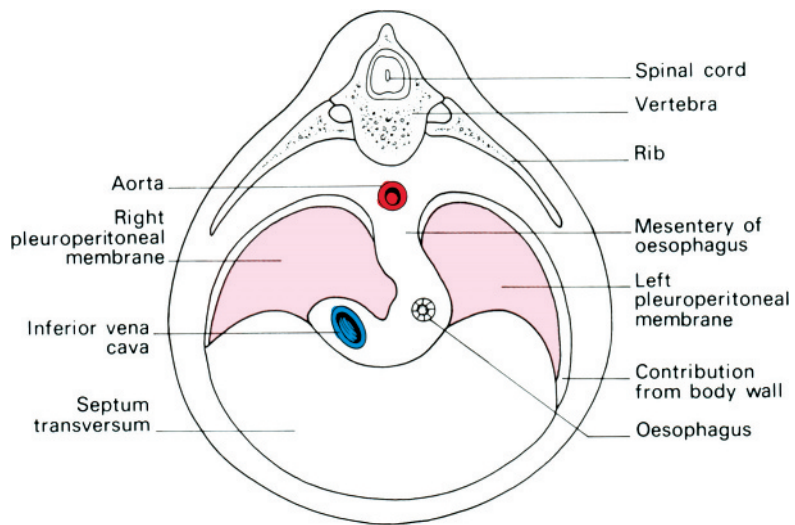


Fig. 64 The development of the diaphragm.

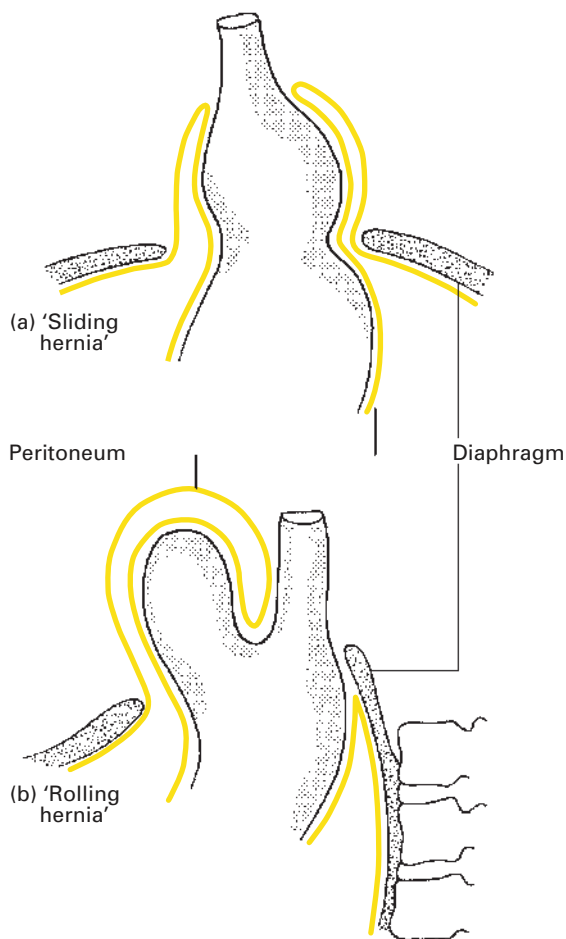


Fig. 65 (a) A sliding hiatus hernia and (b) a rolling hiatus hernia.

78 The respiratory pathway, lungs, thoracic wall and diaphragm

respectively, thus accounting for the long course of the phrenic nerve from the neck to the diaphragm.

In spite of such a complex story, congenital abnormalities of the diaphragm are unusual. However, a number of defects may occur, giving rise to a variety of congenital herniae through the diaphragm. These may be:

- 1 through the foramen of Morgagni – anteriorly between the xiphoid and costal origins;
- 2 through the foramen of Bochdalek – the pleuroperitoneal canal – lying posteriorly;
- 3 through a deficiency of the whole central tendon (occasionally such a hernia may be traumatic in origin);
- 4 through a congenitally large oesophageal hiatus.

Far more common are the acquired hiatus herniae, divided into sliding hernia and rolling hernia. These occur in patients usually of middle age, in whom weakening and widening of the oesophageal hiatus has occurred (Fig. 65).

In the *sliding hernia*, the upper stomach and lower oesophagus slide upwards into the chest through the lax hiatus when the patient lies down or bends over. In the *rolling hernia* (which is far less common), the cardia remains in its normal position and the cardio-oesophageal junction is intact, but the fundus of the stomach rolls up through the hiatus in front of the oesophagus, hence the alternative term of para-oesophageal hernia.