

Phrenic Nerve

Embryology and development

Respiratory system: Thoracic wall and pleural cavities

Whereas the preceding account describes the morphological and histological development of the respiratory tree, for the lungs to function they must be surrounded by a complete pleural cavity slightly larger than the capacity of the lungs. The development of the thoracic cage and the pleural cavities is therefore of vital importance for the functioning of the respiratory system.

At the same time as the splanchnopleuric mesenchyme is being produced from the proliferating coelomic epithelium so too is the somatopleuric. This latter mesenchyme is penetrated by the developing ribs which arise from the thoracic sclerotomes. In the midline the somatopleuric mesenchyme gives rise to the sternum and costal cartilages. The bony and cartilaginous cage provides insertions for the intercostal muscles which arise from the ventrolateral edge of the epithelial plate of the somites. The somatopleuric coelom epithelium after its proliferative phase gives rise to the parietal layer of pleura.

When the lung buds develop they project into the pericardio-peritoneal canals subdividing them into primary pleural coeloms around the lung beds cranially, and paired peritoneal coeloms caudally which are continuous with the wider peritoneal coelom around the mid- and hindgut. The communications with the pericardial and peritoneal coeloms become the pleuropericardial and pleuroperitoneal canals respectively. (When separation between these fluid-filled major coelomic regions is advancing towards completion, they are named the pericardial, pleural and peritoneal cavities; the serous walls of the latter are often called sacs. In early embryos the cavities retain substantial volumes of fluid and their walls are separate; they provide the route for a primitive type of circulation until superseded by the blood vascular system. In later fetal and postnatal life cavity walls are coapted, a mere microscopic film of serous fluid intervening.)

A curved elevation of tissue, the pulmonary ridge, develops on the lateral wall of the pleural coelom and partly encircles the pleuropericardial canal. The ridge is continuous with the dorsolateral edge of the septum transversum. The developing lung bud abuts on the ridge, which as a result divides into two diverging membranes meeting at the septum transversum. One is cranially placed and termed the pleuropericardial membrane; embedded within it the common cardinal vein and phrenic nerve reach the septum transversum by this route. The other membrane, caudally placed, is termed the pleuroperitoneal membrane. As the apical part of the lung forms it invades and splits the body wall and extends cranially on the lateral aspect of the common cardinal vein, carrying with it, or rather preceded by, an extension from the primary pleural coelom to form part of the secondary or definitive pleural sac. In this way the common cardinal vein and the phrenic nerve come to lie medially in the mediastinum. The pleuropericardial canal, which lies medial to the vessel, is gradually narrowed to a slit, which is soon obliterated by the apposition and fusion of its margins. Its closure occurs early and is mainly effected by the growth and expansion of the surrounding viscera, heart and great vessels, lungs, trachea and oesophagus, and not by active growth of the pleuropericardial membrane across the opening to the root of the lung.

In addition to its extension in a cranial direction the lung and its associated visceral and parietal pleura also enlarge ventromedially and caudodorsally (see below). With the ventromedial extension, the lungs and pleurae therefore excavate and split the somatopleuric mesenchyme over the pericardium, separating the latter from the ventral and lateral thoracic walls. Thus the ventrolateral fibrous pericardium, parietal serous pericardium and mediastinal parietal pleura, although topographically deep, are somatopleuric in origin.

Separation of pleural and peritoneal cavities is effected by development of the diaphragm. The septum transversum is at first a condensation of mesenchyme, caudal to the pericardial cavity and extending from the ventral and lateral regions of the body wall to the foregut. Dorsal to it on each side is the relatively narrow pleuroperitoneal canal. The endodermal hepatic bud grows into the septum transversum, which then can be seen to consist of two parts. One, the pars diaphragmatica, is disposed in the transverse plane and lies over the convex cranial surface of the putative liver. The other, the pars mesenterica, lies initially in the median sagittal plane and is expanded by the developing liver. At this stage the liver is widely attached to the pars diaphragmatica and to the ventral abdominal wall. These attachments are the forerunners of the coronary and triangular ligaments and of the falciform ligament respectively. Medial to the pleuroperitoneal canals are the oesophagus and

stomach with their dorsal mesentery, and, at the root of the latter, the dorsal aorta. Dorsolateral to the canals are the pleuroperitoneal membranes, which remain small; dorsally are the mesonephric ridges, suprarenals and gonads. Just as the enlargement of the pleural cavity cranially and ventrally is effected by a process of burrowing into the body wall, so its caudodorsal enlargement is effected in the same way. The expanding pleural cavities extend into the mesenchyme dorsal to the suprarenal glands, the gonads and (degenerating) mesonephric ridges. Thus somatopleuric mesenchyme is peeled off the dorsal body wall to form a substantial portion of the dorsolumbar part of the diaphragm. The pleuroperitoneal canal is closed by the fusion of its edges, which are carried together by growth of the organs surrounding it and, in particular, that of the suprarenal, which carries the dorsal margin of the canal ventrally to meet the pars diaphragmatica of the septum transversum (Wells 1954). The right pleuroperitoneal canal closes earlier than the left. Hence it is on the left that an abnormal communication persisting between the pleural and peritoneal cavities is encountered more frequently. While these changes occur, the septum transversum undergoes a progressive alteration in relative position. In a 2-mm human embryo, the dorsal border of the septum transversum lies opposite the second cervical segment but, as the embryo grows and the heart enlarges, it migrates caudally. At first the ventral border moves more rapidly than the dorsal, but after the embryo has attained a length of 5 mm it is the dorsal border which migrates more rapidly. When the dorsal border of the septum transversum lies opposite the fourth cervical segment, the phrenic nerve (C3, 4 and 5) and portions of the corresponding myotomes grow into it and accompany it in its later migrations. It is not until the end of the second month that the dorsal border of the septum transversum is opposite the last thoracic and first lumbar segments, the final position occupied by some of the dorsal attachments of the diaphragm and some derivatives of the pars mesenterica. However, the main derivatives of the pars diaphragmatica lie at considerably more cranial levels.

Anterolateral muscles and fasciae of the neck

M. Sternocleidomastoideus

Sternocleidomastoid descends obliquely across the side of the neck and forms a prominent surface landmark, especially when contracted. It is thick and narrow centrally, and broader and thinner at each end. It is attached inferiorly by two heads. The medial or sternal head, a rounded tendinous fasciculus, arises from the upper part of the anterior surface of the manubrium sterni and ascends posterolaterally. The lateral or clavicular head, which is variable in width and contains muscular and fibrous fasciculi, ascends almost vertically from the superior surface of the medial third of the clavicle. The two heads are separated near their attachments by a triangular interval which corresponds to a surface depression, the lesser supraclavicular fossa. As they ascend, the clavicular head spirals behind the sternal head and blends with its deep surface below the middle of the neck, forming a thick, rounded belly. The muscle inserts superiorly by a strong tendon into the lateral surface of the mastoid process from its apex to its superior border, and by a thin aponeurosis into the lateral half of the superior nuchal line. The clavicular fibres are directed mainly to the mastoid process; the sternal fibres are more oblique and superficial, and extend to the occiput. The direction of pull of the two heads is therefore different, and the muscle may be classed as 'cruciate' and slightly 'spiralized'.

Relations

The superficial surface of the muscle is related to skin and platysma; between the surface and platysma lie the external jugular vein, the great auricular and transverse cervical nerves and the superficial lamina of the deep cervical fascia. Near its insertion the muscle is overlapped by a small part of the parotid gland. The deep surface of the muscle is, near its origin, related to the sternoclavicular joint, sternohyoid, sternothyroid and omohyoid. The anterior jugular vein crosses deep to it, but superficial to the infrahyoid muscles, immediately above the clavicle. The carotid sheath and the subclavian artery are deep to these muscles. Between omohyoid and the posterior belly of digastric, the anterior part of sternocleidomastoid lies superficial to the common, internal and external carotid arteries, the internal jugular, facial and lingual veins, the deep cervical lymph nodes, the vagus nerve and the rami of the ansa cervicalis. The sternocleidomastoid branch of the superior thyroid artery crosses deep to the muscle at the upper border of omohyoid. The posterior part of sternocleidomastoid is related on its internal surface to splenius, levator scapulae and the scaleni, the cervical plexus, the upper part of the brachial plexus, the **phrenic** nerve and the transverse cervical and suprascapular arteries. The occipital artery crosses deep to the muscle at, or under cover of, the lower border of the posterior belly of digastric. At this point the accessory nerve passes deep to sternocleidomastoid; it pierces (and supplies) the muscle, and reappears just above the middle of the posterior border. At its insertion the muscle lies superficial to the mastoid process, splenius, longissimus capitis and the posterior belly of digastric.

Nerve Supply

Accessory nerve and branches from the ventral rami of the second, third and sometimes fourth cervical spinal nerves. For some time these cervical rami were believed to be solely proprioceptive, but clinical evidence suggests that some of their fibres are motor.

Actions

Acting alone, one sternocleidomastoid will tilt the head towards the ipsilateral shoulder, simultaneously rotating the head so as to turn the face towards the opposite side. This movement occurs in an upward, sideways glance, but a much more common visual movement is a more or less level rotation from side to side, and this probably represents the most frequent use of the sternocleidomastoids. Acting together from below, the muscles draw the head forwards and so help the longi colli to flex the cervical part of the vertebral column. This movement is common in feeding. The two muscles are also used to raise the head when the body is supine. With the head fixed, they help to elevate the thorax in forced inspiration. Electromyographic observations (e.g. de Sousa 1973) suggest that the sternal fibres are more active in contralateral rotation, but that both parts of the muscle are involved to some extent in all of the above movements. This study also indicates that the muscle is involved in extension as well as flexion of the neck.

Clinical Relevance

Torticollis (or wryneck), a postural deformity of the neck, is due to a permanent contracture of the sternocleidomastoid. Spasmodic torticollis, a condition that can develop in adult life, begins with tonic or clonic spasm of one sternocleidomastoid muscle, followed by a spasm of trapezius, particularly its clavicular portion. Such abnormal conditions illustrate the action of the muscle in isolation, but this is a

caricature of its ordinary activities, which are invariably modified by synergists and antagonists, such as splenius capitis.

M. Scalenus anterior

Scalenus anterior lies at the side of the neck deep (posteromedial) to sternocleidomastoid. Above, it is attached by musculotendinous fascicles to the anterior tubercles of the transverse processes of the third, fourth, fifth and sixth cervical vertebrae. These converge, blend and descend almost vertically, to be attached by a narrow, flat tendon to the scalene tubercle on the inner border of the first rib, and to a ridge on the upper surface of the rib anterior to the groove for the subclavian artery.

Relations

Anterior are the clavicle, subclavius, sternocleidomastoid, omohyoid, the lateral part of the carotid sheath, the transverse cervical, suprascapular and ascending cervical arteries, the subclavian vein, the prevertebral fascia and the **phrenic** nerve. Posterior are the suprapleural membrane, the pleura, the roots of the brachial plexus and the subclavian artery; the latter two separate the muscle from scalenus medius. Below its attachment to the sixth cervical vertebra, the medial border of the muscle is separated from longus colli by an angular interval in which the vertebral artery and vein ascend to reach the foramen transversarium of the sixth cervical vertebra. The inferior thyroid artery crosses the interval from the lateral to the medial side near its apex. The sympathetic trunk and its cervicothoracic ganglion are closely related to the posteromedial side of this part of the vertebral artery. On the left side the thoracic duct crosses this triangular interval at the level of the seventh cervical vertebra and usually comes into contact with the medial edge of scalenus anterior. The musculotendinous attachments of scalenus anterior to anterior tubercles are separated from those of longus capitis by the ascending cervical branch of the inferior thyroid artery.

Nerve Supply

Branches from the ventral rami of the fourth, fifth and sixth cervical spinal nerves.

Actions

Acting from below, scalenus anterior bends the cervical portion of the vertebral column forwards and laterally and rotates it towards the opposite side. Acting from above, the muscle helps to elevate the first rib.

Clinical Relevance

The proximity of the muscle to the lower brachial plexus, subclavian artery and vein can give rise to compression syndromes (Katirji & Hardy 1995).

Nervous system

Spinal medulla or cord: grey matter of the cord

Spinal grey matter is a complex mixture of neurons and neurites, neuroglia and blood vessels. The predominance of neuronal somata is responsible for the so-called grey appearance. Neuroglia form an intricate lattice among the somata and their neurites, being particularly condensed in the gelatinous substance around the central canal. Neurites will be described in detail later, with the tracts and with the organization of interneurons; they include axons arriving from or departing to the fibre tracts of the white funiculi, the initial part of efferent peripheral fibres and the termination of afferent peripheral fibres together with their collaterals, and a most complex neuropil. The latter is composed of many neurites of neurons which are mainly confined to the grey matter. Many neurites cross the midline in the commissures, and the right and left halves of the cord, including its grey matter, are a functional continuum. Neurons in the grey substance are multipolar, varying in size and in other features, particularly length and the arrangement of axons and dendrites. Many are Golgi types I and II neurons, axons of the former passing out of the grey matter into ventral spinal roots or spinal tracts. Axons and dendrites of Golgi type II neurons are largely confined to the nearby grey matter. Some neurons are intrasegmental, deployed within a single segment; others spread through several segments, thus being intersegmental in distribution.

In much of the central nervous system, nerve cell somata are grouped, often in large numbers, usually indicating a common function. A large group may be divided with a constancy justifying specific names. Such constant patterns of distribution inevitably suggest functional implications, though the influence of developmental constraints may sometimes be of greater significance. Neurons of the spinal grey matter are not distributed uniformly: they occur in major and minor aggregations, some of which have obvious functional significance, whilst others are subject to controversy. The following cytoarchitecture of the spinal grey substance is first described in purely topographical terms and, for convenience, separately in ventral, dorsal and lateral grey columns. Functional interpretations of some groups in these columns will be considered later.

Neuronal Groups of the Anterior Grey Columns

Neurons in the ventral columns vary in size. The average dimensions of the largest somata of multipolar cells exceed 25 μm ; their axons emerge in ventral roots to innervate the striated skeletal muscles as α -efferents. Large numbers of smaller neurons of 15–25 μm also occur and some of their axons are g -efferents innervating the intrafusal fibres of neuromuscular spindles. By the evidence of retrograde degeneration, many smaller neurons in this column do not have such efferents and most are interneurons.

The ventral column neurons are arranged in elongated groups, forming a number of separate longitudinal columns extending through several segments. These are seen most easily in transverse sections; although longitudinal sections are rarely depicted, these clearly show that the neuronal columns are not uniformly continuous, each is a series of small aggregations, too diminutive for segmental significance (Laruelle & Reumont 1933). The basic division of the ventral grey region is into medial, central and lateral columns and all exhibit subdivision at certain levels, usually into dorsal and ventral parts. As can be seen in medial group extends throughout the cord, being perhaps absent in the fifth lumbar and first sacral segments. In the thoracic and the upper four lumbar segments, it is subdivided into ventromedial and dorsomedial groups; in segments cranial and caudal to this, the medial group has only a ventromedial moiety, except in the first cervical where only the dorsomedial group exists. The central group, the least extensive, is found only in some cervical and lumbosacral segments. In the cervical cord, through the third to seventh segments, is a centrally situated columnar **phrenic** nucleus; abundant experimental and clinical evidence shows that its neurons innervate the diaphragm, being probably the least controversial motor pool in the entire cord. For experimental data in mammals, including primates, see Kohnstamm (1898), Sharrard (1955), Keswani and Hollinshead (1956), Warwick and Mitchell (1956), Ullah (1978), and Kuypers (1985). The lumbosacral nucleus, in the second lumbar to first sacral segments, is also central; the distribution of its axons is unknown. Neurons whose axons are said to enter the spinal accessory nerve form an irregular accessory group, in the upper five or six cervical segments, at the ventral border of the anterior grey column and intermediate in position but lateral to the dorsomedial group in the first cervical segment; the ventral siting of this nucleus may be due to the absence of lateral groups from the first three cervical segments.

The lateral group in the ventral column is subdivided into ventral, dorsal and retrodorsal groups, all largely confined to the spinal segments innervating the limbs. Their extents are indicated in 8.95 and

their significance will be discussed later. Onufrowicz (1899), who later called himself Onuf, described a ventrolateral group in the first and second sacral segments, considered to innervate the perineal striated muscles. This 'nucleus of Onuf' has been confirmed in mankind by Mannen et al (1977) and Schroder (1981), and by Konishi et al (1978) and Holstege and Tan (1987) in cats (see p. 1078).

Neuronal Groups of the Posterior Grey Columns

Two groups are in the dorsal regions of spinal grey matter extending the whole length of the cord and two are limited to the thoracic and upper lumbar segments. No less than 15 neuromediators have been identified in the spinal dorsal grey column.

Substantia gelatinosa (of Rolando), present at all levels, consists of small Golgi type II neurons with some larger ones. Connections with afferents of the dorsal roots and the spinothalamic tract complex have long been accepted, but a revision of the details has followed experimental work (pp. 986–990). A second long group of large neurons, ventral to the substantia, is the dorsal funicular group or nucleus proprius. A thin lamina of neurons, distinguishable from those of the substantia by their larger size, is the marginal zone of some observers, sited dorsal to the substantia.

Nucleus dorsalis or thoracicus ('Clarke's column') is basal in the posterior grey column, immediately dorsal to the intermediate zone in laminae VI–VII. At most levels, it is near the dorsal white funiculus and may project into it. In the human spinal cord, it can usually be identified from the eighth cervical to the third or fourth lumbar segments. Similar groups have been described at cervical levels superior to the nucleus dorsalis; also prolongations at caudal levels appear to exist in some long-tailed monkeys (Chang 1951). But these 'cervical' and 'sacral' nuclei consist of different neurons and have been described only in some mammals; hence it is premature to extrapolate such groups to the human spinal cord. Neurons of the dorsal nucleus itself vary, most being large, especially in the lower thoracic and lumbar segments; some send axons into the dorsal spinocerebellar tracts (p. 990) while some are interneurons. Petras and Cummings (1977) have described the neurons and connections of this nucleus in neonatal dogs, confirming a role as a 'relay' in the dorsal spinocerebellar paths; they ascribed a similar role to the nucleus centrobasis, which is in the dorsal grey column like the nucleus thoracicus, but situated in the lower cervical and lumbosacral segments. These groups have not been established in human spinal cord.

Lateral to the nucleus dorsalis and dorsal to the intermediolateral column, a small region of neurons of medium size extends through the same segments (first thoracic to third lumbar) as the intermediate columns (Takahashi 1913); this group is identifiable in the human cord, but is functionally obscure.

Neuronal Groups of the Intermediate Grey Matter

The intermediate region of spinal grey matter, including the lateral grey columns, contains small neurons, many with the features of autonomic preganglionic cells. These develop in the embryonic cord at first dorsolateral to the central canal. Many migrate lateral to it, forming an intermediolateral column. An intermediomedial column is formed from neurons nearer the central canal. The intermediolateral is the projecting lateral grey column proper; many of its neurons send axons into ventral spinal roots and via white rami communicantes to the sympathetic trunk. Preganglionic fibres are similarly derived from some cells of the intermediomedial column (the remainder being interneurons). Both groups extend from the eighth cervical or first thoracic segment to the second or third lumbar, corresponding approximately to the thoracolumbar outflow. In the second to fourth sacral segments a similar group, intermediate in position, is the source of the sacral outflow of parasympathetic preganglionic nerve fibres. This sacral parasympathetic grey column also lies lateral to the central canal and substantia gelatinosa centralis in the zone between the bases of the anterior and posterior grey columns and shows no mediolateral division, nor does it project like the thoracolumbar lateral grey column. The emergence of parasympathetic preganglionic nerve fibres from other segments has been described by Kuré et al (1930) and Sheehan (1933), their origins being ascribed to the basal region of the dorsal grey column and perhaps the intermediate grey zone; the fibres were stated to issue in the dorsal roots, to be vasodilator and to synapse in the corresponding dorsal spinal root ganglia (Kiss 1932; Kuré et al 1934). These interesting views have received neither general acceptance nor confirmation.

This description of spinal cytoarchitecture largely depends on material stained to show the somata of neurons rather than their processes; it has been amplified by a laminar concept of spinal organization. More widely based on interconnections, its structural data are correlated with the results of degeneration experiments and microelectrode studies. The laminar pattern yields a more precise definition of spinal cord activities; but the two modes of description are not exclusive, the older scheme of columnar groups being in most features adaptable into the newer description. The main modifications concern the structural relations between the dorsal grey column neurons and the fibres of dorsal roots and spinal tracts.

Pain and nociception

Pain and Nociception

It is nearly a century since the publication of Sherrington's influential work 'The integrative action of the nervous system'. What is surprising is how little the conceptual ideas about pain mechanisms changed over most of that period, and how much they have changed in the last few years.

For most of this century, textbooks have expounded a view with its roots in the writings of Descartes and couched in neurophysiological terms by Sherrington, who wrote that 'Pain appears the psychological adjunct to protective reflexes'. He (as Descartes before him) envisaged pain as an alarm system, triggered by stimuli which threaten or damage the body, and drive avoidance behaviour. Sherrington postulated the existence of nociceptors, sensory neurons that would not respond to normal physiological events or innocuous stimuli, but would be recruited specifically by immediate threats. With this guidance researchers sought and found evidence for just such a population of afferent neurons, initially in skin and then in deep somatic tissues. There was a lag of several decades, however, because of the technical difficulties in making recordings from these thin fibres (conducting in the Ad and C range of velocities). These findings were seen as vindicating the so-called specificity theory, over its rival, the pattern theory (which proposed that sensory information was encoded in a combinatorial way in groups of broadly tuned afferent neurons). Parenthetically, recent work on the properties of sensory neurons innervating visceral tissues suggests that specific nociceptors are very rare in many organs, and rather that noxious events are mostly signalled by 'intensity-encoding' neurons that respond to innocuous physiological stimuli and, with a higher frequency of action potential discharge, to noxious ones.

The idea of a specific pathway for pain was by most writers implicitly applied also to the central nervous system. The Gate Control theory of Melzack and Wall was the first serious challenge to the specific pathway theory. This theory emphasized that pain was a subjective experience, dependent on the context in which it occurred and, therefore, modifiable by other events. The particular 'wiring diagram' which illustrated the theory focused on interactions between different afferent fibre types, and proposed that the activity of large diameter innocuous afferents would modify (inhibit) the central transmission of information carried by small diameter fibres.

In the last decade a major shift in thinking has occurred, driven by a recognition that mechanisms of acute pain (also called physiological pain) might differ substantively from those of chronic (also called pathophysiological) pain. It is not so much that earlier facts have been refuted, but rather that their applicability to clinically relevant pain states has been challenged. What has become very clear is that the signalling system is itself strongly modified by the very injury that it reports upon.

This plasticity in the injury-signalling system is being intensively studied at two loci: firstly, at the peripheral terminals of nociceptors; secondly, at the first central site of processing, in the posterior horn of the spinal cord. The changes at these sites are generally referred to as peripheral and central sensitization, respectively.

Peripheral sensitization, as its name implies, relates to an increase in the sensitivity of the peripheral endings of nociceptors. One new development, however, has been the description of a novel class of nociceptors that is not activated by traditional noxious stimuli (i.e. excessive mechanical or thermal stimuli), but which is recruited when tissue becomes inflamed. These sensory neurons have been dubbed 'silent afferents', 'sleeping nociceptors' and, rather more prosaically, 'mechanically insensitive afferents'. They are ubiquitous. In the presence of tissue injury, some of these fibres become mechanosensitive and this is likely to constitute an important new source of afferent barrage. For instance, in an arthritic joint, normally innocuous movements may activate sensitized afferents. These afferent neurons are obviously primarily chemosensitive. The chemical changes in damaged tissue usually persist long after the precipitating cause. These afferents cannot, therefore, function as classical Sherringtonian nociceptors, triggering 'protective reflexes'. A still uncertain issue is exactly what chemical mediators are responsible for recruiting these silent afferents. The list of potential candidates has merely lengthened, actually more a mark of research failure than success. Alongside traditional mediators such as bradykinin, prostaglandins, and serotonin, evidence is growing for the involvement of new molecules—cytokines and growth factors, such as tumour necrosis factor (TNF) and nerve growth factor (NGF).

The second major area of current interest is that of central sensitization. The basis of this phenomenon is that repetitive activity in unmyelinated primary sensory neurons is capable of producing a long-lasting facilitation in the responsiveness of the neurons in the spinal cord that process nociceptive information, which includes a lowering of the threshold of peripheral stimuli necessary to excite the cells. The process provides a ready explanation for some features of the

increased sensitivity that is commonly seen after tissue damage in man (so-called hyperalgesia, some aspects of which, such as spread around a focal peripheral lesion, are not easily explained by peripheral mechanisms). The significance of the time course of central sensitization (prolonged action after only a brief initiating stimulus) is, of course, that the principal site of pathophysiology in persistent pain states may effectively move from a peripheral to a central locus, and attempts to 'correct' a peripheral pathology may be futile. It is also notable that the role of large tactile afferents changes from inhibitory to excitatory as one moves from the normal to the injured state.

Central sensitization appears to be a very general phenomenon, and has been seen in a large number of models of persistent pain and under a wide variety of conditions. Rather remarkably, all forms of central sensitization seen to date share a common pharmacology. It is now known that most primary sensory neurons release excitatory amino acids (glutamate and aspartate) as neurotransmitters. There are different classes of receptors for these transmitters. Most second-to-second signalling in spinal cord neurons appears to depend critically on one receptor subtype (the so-called α -amino-3-hydroxy-5-methyl-4-isoxalone propionic acid (AMPA) receptor). In contrast, the various manifestations of central sensitization depend on a different subtype—the N-methyl-D-aspartate (NMDA) receptor. Hence, blockade of NMDA receptors has little effect on sensory processing under resting conditions, but completely prevents central sensitization. The reason for this dichotomy appears to be that the NMDA receptor is only recruited during repetitive firing in unmyelinated afferents. Once recruited, however, it allows Ca^{2+} to enter the postsynaptic cell, and this in turn triggers a cascade of change that maintains the central hyperexcitable state. One of the second messengers activated by the increased intracellular Ca^{2+} levels under these conditions is nitric oxide (NO), a diffusible transmitter the production of which also appears to be critical for the development of central sensitization. It is interesting just how many parallels there are between these changes in spinal cord function in persistent pain states, and other forms of neuronal plasticity in the adult nervous system, such as long-term potentiation in the hippocampus.

This new knowledge is changing the emphasis of those interested in developing therapies to help treat patients in pain. There is a growing realization that rather than seek analgesic drugs (which aim to block injury-related neuronal signals at some point), there is a great opportunity to develop a new class of agents that are actually antihyperalgesic. Such drugs will, it is hoped, restore the signalling system to its normal level of excitability, and, therefore, retain the protective features of the pain signalling system.

Unit Recording with Intracellular Microelectrodes

Recordings from microelectrodes inserted into individual neurons have provided much information about their properties and activities. Neurons contributing axons to long tracts, such as the spinothalamic, have a complex functional organization and are generally classified according to the types of cutaneous or deep afferent stimuli that activate them. Low-threshold (LT) units are neurons which respond only to either hair movement or gentle cutaneous pressure, and do not increase their firing rate when more intensely noxious stimuli are applied. Wide dynamic range (WDR) units are activated by hair movement or gentle mechanical stimulation, but, in addition, increase their activities when noxious stimuli are applied to the skin, so that they respond maximally to noxious stimuli. High-threshold (HT) units refer to neurons that respond only to intense mechanical or thermal stimulation of the skin. Neurons receiving stimulation from deeper tissues (muscles, tendons or joints) are designated deep (D) units. Other functional subclasses within these classes are also defined. Some neurons that receive exclusively or additionally visceral input are termed visceral specific or somatovisceral units respectively; others that record innocuous warming or cooling of their receptive fields are thermoreceptive units.

Comparison of the Dorsal Column–Medial Lemniscus Complex with the Spinothalamic Path

It is instructive to compare, in these two 'systems', the size of the receptive fields, somatotopy, specificity of channels, and forms of control of transmission.

Neurons of Dorsal Column Nuclei

Neurons of dorsal column nuclei (Mountcastle 1968; Norton 1968) receive terminals of long, uncrossed, primary afferent fibres of the fasciculi gracilis and cuneatus, which carry information concerning deformation of skin, movement of hairs, joint movement and vibration. In the cat, fibres from hair receptors are superficial, those for touch and vibration more deeply placed. The somatotopy of fibres in the dorsal white columns has been noted; the connections of dorsal column nuclei are further detailed with the medulla oblongata.

Unit recording in the neurons of dorsal column nuclei shows that their tactile receptive fields (i.e. the skin area in which a response can be elicited) vary in size, being mostly small and smallest in the digits. Some fields have excitatory centres and inhibitory surrounds; thus stimulation just outside its field inhibits the neuron. Neurons in the nuclei are spatially organized into a somatotopic map of the

periphery (in accord with the similar localization in the dorsal columns). In general specificity is high. Many cells receive input from one or a few specific receptor types, for example hair, type I and II slowly adapting receptors and Pacinian corpuscles; some cells respond to Ia muscle spindle input. However, some neurons do receive convergent input from tactile pressure and hair follicle receptors. The transmission of impulses through the dorsal column–medial lemniscus pathway is subjected to a variety of control mechanisms (Jabbur & Towe 1961; for review see Willis & Coggeshall 1991). Concomitant activity in adjacent dorsal column fibres may result in presynaptic inhibition by depolarization of the presynaptic terminals of one of them. Stimulation of the sensory–motor cortex also modulates the transmission of impulses by both pre- and postsynaptic inhibitory mechanisms, and sometimes by facilitation. These descending influences are mediated by the corticospinal tract. Modulation of transmission by inhibition also results from stimulation of the reticular formation, raphe nuclei and other sites.

The dorsal column nuclei are not merely 'relay nuclei', as was long supposed. They have been pictured as a highly reliable telephone system in which afferent information is separated in channels which are discrete both for spatial origin and stimulus specificity. In this the dorsal columns strongly contrast with the spinothalamic tracts (see below).

Neurons of the Spinothalamic Tract

Neurons of the spinothalamic tract have very different receptive fields (see below). Specificity of separate channels, as it exists in the dorsal column nuclei, is absent in the laminae of the cord. Convergence of different functional types of afferent fibres onto an individual tract cell is a common feature in the cord. On the basis of laminar site, functional properties and specific thalamic termination of their axons, spinothalamic tract neurons may be divided into three separate groups, namely:

- apical cells of the dorsal grey column (lamina I)
- deep dorsal column cells (laminae IV–VI)
- cells in the ventral grey column (laminae VII, VIII).

Although there are species differences the data given below pertain to the monkey. For a critical review on the spinothalamic tract and its neurons see Hodge and Apkarian (1990).

Lamina I cells projecting to the thalamus show the following characteristics. In essence they respond maximally to noxious or thermal cutaneous stimulation, and consist mainly of high threshold, but also some wide dynamic range units. Their receptive fields are usually small, comprising a part of a digit or a small area of skin involving several digits. Lamina I spinothalamic tract neurons receive input from A-d and C fibres, and some respond to convergent input from deep somatic and visceral receptors. Marked viscerosomatic convergence is shown in spinothalamic tract cells in the thoracic cord. Lamina I spinothalamic tract neurons project preferentially to the ventroposterolateral nucleus of the thalamus with limited projections to the centrolateral and mediodorsal thalamic nuclei.

Deep dorsal column (laminae IV–VI) spinothalamic neurons studied in the lumbar cord comprise 60% wide dynamic range, 30% high threshold, and 10% low threshold type units. They can code accurately both innocuous and noxious cutaneous stimuli. Some cells respond also to input from deep somatic and visceral receptors. In the lumbar cord their receptive fields are small or medium sized, being larger than the area of the foot but smaller than the entire leg; in the thoracic cord the fields of these laminar cells are larger, often including the entire upper limb plus part of the chest. Many of the deep dorsal column spinothalamic tract neurons in the thoracic segments receive convergent input from sympathetic afferent fibres. Laminae IV–VI spinothalamic tract units project to either the ventroposterolateral (VPL) nucleus or to the centrolateral nucleus of the thalamus, and sometimes to both nuclei. Units projecting to the ventroposterolateral nucleus receive input from all classes (A-b, A-d and C) of cutaneous fibres.

Ventral grey column (laminae VII and VIII) spinothalamic tract cells respond mainly to deep somatic (muscle and joint) stimuli, but also to innocuous and/or noxious cutaneous stimuli. In the thoracic regions of the spinal cord they also receive convergent input from visceral sources. The majority of laminae VII and VIII spinothalamic tract neurons have large, complex receptive fields (often bilateral) which encompass widespread areas of the body. Cells of this group that project exclusively to the medial thalamus receive input from A-b, A-d, and C classes of afferent fibres, and many respond to convergent input from receptors of deep structures. These neurons were found to comprise 25% wide dynamic range, 63% high threshold, and 12% low threshold or deep type. Most of the spinothalamic tract cells in the ventral grey column project to the intralaminar nuclei of the thalamus.

Note that the wide dynamic range type neurons are particularly effective for the discrimination of different intensities of painful stimulation. Furthermore, it is suggested that the spinothalamic projection to the ventroposterolateral nucleus is concerned with the discriminative aspects of pain perception, whereas the projection to other thalamic regions, particularly the intralaminar nuclei, may be involved in arousal and/or aversive behaviour.

The control of impulse transmission is modulated in a variety of ways. First, the cutaneous afferents are influenced by a tonic regulating mechanism in the substantia gelatinosa described previously; additionally, transmission is influenced by a variety of descending fibres from the sensory–motor cortex and brainstem centres.

The roles of dorsal columns and spinothalamic tracts have aroused much controversy. The classic view (Mountcastle 1968) regards the dorsal columns as the essential discriminatory pathway, without which a mechanical stimulus is recognized but assigned no specific location, intensity or pattern. This view is strongly challenged (Wall 1970; Wall & Noordenbos 1977) because complete section of the dorsal column does not abolish discrimination of weight, texture, two-point stimulation, vibration or position (but see Nathan et al 1986). Environmental stimuli may be classified into those 'passively impressed' and those which 'must be actively explored by motor movement or sequential analysis' for successful discrimination. The former is considered the spinothalamic role, that of the dorsal columns is to initiate and plan exploration of the stimulus for the subsequent transmission of information.

Spinal Terminations of Tracts Descending from Supraspinal Sources

Degeneration techniques such as Nauta's have much illuminated the spinal terminations of descending tracts (Nyberg-Hansen 1964a, b, 1965b, 1966a, b, 1969; Nyberg-Hansen & Brodal 1963, 1964; Nyberg-Hansen & Mascitti 1964; Brodal 1969). Most investigations have been in cats, rarely primates. Results, while probably generally applicable, cannot be transferred in toto to human structures. The principal findings are summarized in 8.119, in which the distributions of terminals are related to laminar architecture. The following points, some already mentioned, are noteworthy.

Corticospinal Fibres

Almost all these terminate, in cats, on interneurons in laminae IV–VII; but because of the widespread dendrites of multipolar neurons in lamina IX, which penetrate lamina VII, the existence of a few axodendritic contacts with motor neurons cannot be ignored. Corticospinal fibres from the 'sensory' cortex terminate chiefly in laminae IV and V, those from the 'motor' cortex in V–VII, with the densest concentration laterally in lamina VI. Thus, despite some overlap, corticospinal fibres from these two regions end differently—findings of interest in view of increasing evidence involving corticospinal tracts in the supraspinal modulation of sensory inflow; this may be mediated by presynaptic inhibition of primary afferent terminals or the postsynaptic inhibition or facilitation of subsequent neurons. In contrast, there is anatomical (Hoff & Hoff 1934; Kuypers 1960; Liu & Chambers 1964) and physiological (Bernhard et al 1953; Preston & Whitlock 1961; Landgren et al 1962) evidence, that in monkeys some corticospinal fibres end monosynaptically on large α motor neurons (see p. 1000). Less is known quantitatively about human synaptic terminals; most end on interneurons but many end directly on motor neurons. Physiological studies (Corazza et al 1963) indicate that feline corticospinal tracts influence α and γ motor neurons, mainly via interneurons. The increased flux of impulses in corticospinal axons is excitatory to motor neurons of flexors and inhibitory to those supplying extensors. Converse effects of decreased flux are equally essential in normal function.

Rubrospinal Fibres

These arise from large and small neurons in the contralateral red nucleus, with some degree of somatotopic order. Degeneration after nuclear lesions in cats shows the tract descending to lumbosacral levels, with terminals on interneurons in laminae V–VII. Its terminal zones correspond to those of corticospinal fibres from the 'motor' cortex, with similar effects on α and γ motor neurons. In some animals a somatotopic corticorubral projection has been demonstrated from the sensory–motor cortex, suggesting dual routes from cortex to cord, direct corticospinal and indirect corticorubrospinal, with similar spinal terminations and common functions. But the origin, localization, termination and functions of human rubrospinal connections are poorly defined, and the tract appears to be rudimentary.

Vestibulospinal Tracts

Medial and lateral are much investigated in other animals, but are less clarified in man. The lateral, from the ipsilateral lateral vestibular nucleus, descends the whole cord, ending at successive levels largely in laminae VII and VIII and less so in lamina IX. The medial tract, mainly from both medial vestibular nuclei, descends perhaps only to midthoracic levels, terminating less widely in parts of laminae VII and VIII. Activation of the lateral tract excites extensor and inhibits flexor motor neurons. Excitation is monosynaptic, indicating that vestibulospinal terminals synapse with the extensive dendrites of some motor neurons penetrating laminae VII and VIII. Gamma motor neurons are also probably facilitated; the inhibitory effect on flexors is presumably by inhibitory interneurons in their laminae of termination.

Reticulospinal Tracts

Notably difficult to evaluate in human spinal cords, these have been mainly examined in cats, by retrograde degeneration in spinal neurons after spinal trauma and by anterograde effects following brainstem lesions. Pontine and medullary reticulospinal fibres from one side apparently pass to both sides of the spinal cord; the pontine fibres are the more concentrated on the ipsilateral side; the medullary fibres have also a substantial contralateral component. The zones of termination are summarized in 8.120. (For non-aminergic, noradrenergic, serotonergic, enkephalinoid and other neuromediator substances associated with reticulospinal fibres) Similar experiments indicate that tectospinal and interstitiospinal tracts both terminate in laminae VI–VIII.

Summary of Spinal Organization

Szentágothai (1967) has considered spinal grey matter as a central core with paired dorsal and ventral appendages, each with distinctive features, terms which of course cut across the usual description but are held to be less arbitrary. The core has a diffuse, non-discriminative, reticular organization, with great divergence and convergence of paths; most interneurons connect with hundreds, perhaps thousands, of others distributed in a substantial length of cord. In contrast, dorsal and ventral appendages are more discriminatively organized in terms of somatotopy and functional localization. The precise limits to core and appendages are indefinable. The concept will undoubtedly need revision and perhaps lose relevance as knowledge increases. The central core includes interneurons of laminae VII and VIII (i.e. the intermediate zone and the areas between the motor neuron columns). But interneurons of dorsal columns and in motor neuron columns should also be included in this postulated reticular core. The ventral appendage corresponds to the neuronal columns of lamina IX; the dorsal appendage includes laminae I–VI.

Dorsal Appendage

This is a main receptive zone of exteroceptive, proprioceptive and interoceptive dorsal spinal root fibres. Laminae I–IV are the main cutaneous receptive areas; lamina V receives fine afferents from the skin, muscle and viscera; lamina VI receives proprioceptive and some cutaneous afferents. But few appropriate investigations have yet been made; hence the functional boundaries are uncertain and interneuronal complexities are postulated but as yet undemonstrated. Intracellular recording has its difficulties; some neurons may long remain out of technical reach.

Nevertheless, the available recordings suggest that neurons in the dorsal appendages abstract data from internal and external environments. Neuronal groups show varying somatotopic array, size and response of receptive fields, specificity, convergence and interaction. Clearly, simple views of spinal neurons as merely relays in invariant, discrete, 'unimodality' channels, transmitting a punctate replica of the environment to the spinal cord or brain, are inadequate. Complex transformations of input occur in the dorsal appendage, whose output spreads to many destinations: directly to the ventral motor neuron columns, or indirectly, via laminae including complex interneurons of the reticular core, to both sides of the cord, cranial and caudal to the input. Neurons in the dorsal appendage and reticular core contribute to the ascending tracts, reaching many brainstem centres.

Transmission to and through the dorsal appendage may be modified by mutual interaction and control. Facilitatory and inhibitory effects, due to simultaneous activity in various afferent fibres converging on a single neuron, have been noted, as has tonic modulation by the substantia gelatinosa. Much evidence suggests that transmission in all laminae is influenced by supraspinal sources, with excitation or inhibition provided by a wide array of neuromediators. The functional significance of these mechanisms is obscure; they may eliminate redundancy, reduce confusion or be linked to central 'states of readiness' or temporary 'preoccupation' with immediately significant transformations. It is increasingly clear that most descending tracts, which influence motor behaviour, do so indirectly by modifying transmission in the primary afferents, and in interneurons in the spinal laminae, less often than by direct influence on motor neurons.

Interneurons of the Reticular Core

These form an intricate net in which each neuron receives inputs from and transmits to large numbers of others and is characterized by one or more neuromediators. The core receives input from some axons of the dorsal appendage, the proprioceptive dorsal root fibres and some descending fibres. This plethora of connections makes investigation difficult but an earlier view of random nerve networks is receding with newer methods, which include minute stereotactic lesions, intracellular recording, the inspection of thousands of Golgi-stained sections and the mapping of somata or terminals according to their content of established or putative neuromediators. An aspect of organization has emerged that concerns the quantitative analysis of connectivity ('transmitting power') of the different types of

interneurons and some of the descending tracts. Some axonal terminals have very long courses in the grey matter and through successive branches give two or three synaptic end-bulbs to each of many hundreds of interneurons encountered; others concentrate many end-bulbs on one or a small group of neurons; while others have widespread paracrine effects. Diffuse, 'non-discriminative' connections hence contrast with 'discriminative' ones. Many proprioceptive terminals in the core are 'segmentally' localized in transverse 'sheets' of grey matter, in contrast to dorsal appendage cutaneous afferents which terminate in longitudinal sheets. In such complex interneuronal congeries, sensory input probably interacts with supraspinal influences to set in train the multivariuous locomotor responses. This analysis is largely speculative but the modern technical armamentarium will doubtless effect some progress.

Ventral Appendage

This is a columnar array of a and g motor neurons and interneurons. Evidence points to 'tonic' and 'phasic' types of neurons innervating striated muscle and to different types of neurons for 'static' and 'dynamic' responses in muscle spindles and their independent controls; but their detailed synaptic patterns remain uncertain.

The main connections of the motor neurons are:

- direct monosynaptic terminals of proprioceptive dorsal root afferents in the same or nearby segments
- terminals from axonal collaterals from dorsal appendage interneurons
- terminals of interneurons of the reticular core: 'discriminative' from the same segment, 'non-discriminative' from adjacent segments
- direct monosynaptic terminals from the vestibulospinal and (in primates including man)

corticospinal tracts.

The interaction of such converging channels for integrated motor behaviour is obscure. A few generalizations can be made; descending paths can be grouped into those wherein impulses are excitatory to flexors, inhibitory to extensors (cortico-, rubro- and medullary reticulospinal tracts) and those with the opposite effect (vestibulo- and pontine reticulospinal tracts). But this simple dualistic view ignores much investigation reported on the complex modification of reflex activities by descending tracts.

Muscle is made to contract or relax by two routes: the pathway produces a direct, immediate change in the excitatory level of a motor neurons innervating motor units, but probably acts infrequently, in sudden forceful responses; usually a g pathway also operates by sequential activity in local interneurons and activity (or inhibition) of the efferents to muscle spindles which, via local muscle 'servo-loop' mechanism (p. 971), causes the appropriate change in tonic and phasic motor neurons by maintaining or breaking the a-g linkage (Granit 1970). Available reports indicate that during voluntary actions initiation of activity in the a system may be more frequent than previously recognized.

Level of Spinal Injury is a Determinant of Clinical Severity

The segmental level of spinal cord injury may be determined from clinical data and accurate anatomical knowledge. Complete division above the fourth cervical segment causes respiratory failure by the loss of activity in the phrenic and intercostal nerves. Lesions between C5 and T1 paralyse all four limbs (quadriplegia), the effects in the upper limbs varying with the site of injury: at the fifth cervical segment paralysis is complete; at the sixth each arm is positioned in abduction and lateral rotation, with the elbow flexed and the forearm supinated, due to unopposed activity in the deltoid, spinatus, rhomboid and brachial muscles (all supplied by the fifth cervical spinal nerves). In lower cervical lesions upper limb paralysis is less. Lesions of the first thoracic segment paralyse small muscles in the hand and damage the sympathetic outflow, resulting in contraction of the pupil, recession of the eyeball, narrowing of the palpebral fissure and loss of sweating in the face and neck (Horner's syndrome); sensation is retained in areas innervated by segments above the lesion; thus cutaneous sensation is retained in the neck and chest down to the second intercostal space, because this area is innervated by the supraclavicular nerves (C3 and C4). At thoracic levels, division of the cord paralyse the trunk, below the segmental level of the lesion, and both lower limbs (paraplegia). The first sacral neural segment is approximately level with the thoracolumbar vertebral junction; injury, commonly occurring here, paralyse the urinary bladder, rectum and muscles supplied by the sacral segments; cutaneous sensibility is lost in the perineum, buttocks, the back of the thighs and the legs and soles of the feet. The roots of lumbar nerves descending to join the cauda equina may be damaged at this level, causing complete paralysis of both lower limbs. Lesions below the first lumbar vertebra may divide or damage the cauda equina, but severe nerve damage is uncommon and is usually confined to the spinal roots at the level of the trauma. Neurological symptoms may also be due

to interference with the spinal blood supply, particularly in the lower thoracic and upper lumbar segments.

Vertebral Levels of Spinal Cord Segments

The level of spinal segments relative to the vertebrae is clinically important. A useful approximation is: in the cervical region the tip of the vertebral spine corresponds to the succeeding cord segment (i.e. the sixth cervical spine is opposite the seventh spinal segment); at upper thoracic levels a tip of a vertebral spine corresponds to the cord two segments lower (i.e. the fourth spine is level with the sixth segment); in the lower thoracic region there is a difference of three segments (i.e. the tenth thoracic spine is level with the first lumbar segment). The eleventh thoracic spine overlies the third lumbar segment, the twelfth is opposite the first sacral segment. The neonatal spinal cord extends to the upper border of the third lumbar vertebra. Barson and Sands (1970), in a series of 258 pre- and postnatal subjects, found the perinatal level at the third lumbar vertebra, rising during the first 2 postnatal months. Individual variation was marked: first to fourth lumbar at birth, first to third in children (3 months–15 years of age).

Cranial nerve: course of the Vagus nerve

Vagus Nerve

The vagus nerve contains motor and sensory fibres and has a more extensive course and distribution than any other cranial nerve, traversing the neck, thorax and abdomen. It emerges as eight or ten rootlets from the medulla oblongata, below the glossopharyngeal nerve in the groove between the olive and the inferior cerebellar peduncle. It has four nuclei in the medulla oblongata, namely the dorsal nucleus, the nucleus ambiguus, the nucleus tractus solitarius, the spinal trigeminal nucleus.

Dorsal Nucleus

This is a general visceral efferent nucleus with 80% of its neurons giving rise to the parasympathetic preganglionic fibres of the vagus nerve and the remainder being interneurons or projecting centrally (Hopkins 1987). It is the largest parasympathetic nucleus of the brainstem and is sited in the central grey matter of the lower dorsomedial portion of the medulla oblongata close to the floor of the IVth ventricle. It extends caudally to the first cervical spinal segment and rostrally to the open part of the medulla under the vagal triangle and separated from the hypoglossal nucleus by the nucleus intercalatus. Its motor fibres are distributed to the non-striated muscle of the viscera of the thorax (heart, bronchi, lungs and oesophagus) and abdomen (stomach, liver, pancreas, spleen, small intestine and proximal part of the colon). In man, neurons within the nucleus are heterogeneous and can be classified into nine subnuclei that are regionally grouped into rostral, intermediate and caudal divisions (Huang et al 1993). Topographic maps of visceral representation in other species suggest the heart and lungs are represented in the more caudal and lateral part of the nucleus whereas gastric and pancreatic representation occupies intermediate regions and the remaining abdominal organs are represented in the rostral and medial part of the nucleus (Getz & Sirnes 1949; Mitchell & Warwick 1955; Katz & Karten 1985; Laughton & Powley 1987; Hopkins 1987; Okumura & Namiki 1990). There may be a sparse sensory afferent supply which arises in the nodose ganglion and projects directly to the dorsal and lateral edges of the nucleus (Shapiro & Miselis 1985) and possibly beyond into the nucleus tractus solitarius.

Nucleus Ambiguus

Below the origin of the fibres joining the glossopharyngeal nerve, neurons of the nucleus ambiguus contribute fibres to the vagus for distribution to striated muscle: the pharyngeal constrictors, intrinsic laryngeal muscles and striated muscles of the palate and upper oesophagus. The nucleus is connected to corticonuclear tracts bilaterally and to many brainstem centres. There is topographical organization in the dorsal nucleus ambiguus, with the individual laryngeal muscles being innervated by relatively discrete groups in more caudal zones (Szentágothai 1943; Getz & Sirnes 1949; Lawn 1966), those to the pharynx lying in the intermediate group and those to the oesophagus and soft palate being rostral (Holstege et al 1983). Most caudally there is also a group of preganglionic parasympathetic fibres ventrolateral to the main cell column which is the main site of origin of cardioinhibitory neurons (Hopkins 1987).

Nucleus Tractus Solitarius

This receives special visceral gustatory afferents from facial glossopharyngeal and vagus nerves which terminate in a viscerotopic pattern predominantly in the rostral region (Norgren 1978; Hamilton & Norgren 1984). Experimental evidence suggests that fibres from the anterior two-thirds of the tongue and the roof of the oral cavity (via chorda tympani and greater superficial petrosal branches of the facial nerve) terminate in the extreme rostral part of the solitary complex. Those from the circumvallate and foliate papillae of the posterior third of the tongue, tonsils, palate and pharynx (via the lingual branch of the glossopharyngeal nerve) are distributed throughout the rostrocaudal extent of the nucleus tractus solitarius predominantly rostral to the obex whilst gustatory afferents from the larynx and epiglottis in the superior laryngeal branch of the vagus have a more caudal and lateral distribution (Rhoton et al 1966; Hamilton & Norgren 1984; Whitehead 1986). Vagal afferents terminate throughout the nucleus, although the most rostral fibres appear to be somewhat denser laterally (Beckstead & Norgren 1979). The cytoarchitectural characteristics of the subnuclei of the human nucleus tractus solitarius correspond well with the nuclei described in experimental studies (Loewy & Burton 1978; Kalia & Mesulam 1980a, b; Tork et al 1990; Hyde & Miselis 1992). The medial and commissural nuclei in the caudal nucleus tractus solitarius appear to be the primary site of termination for gastrointestinal afferents (Gwyn et al 1979, 1985). Ventral and interstitial subnuclei probably receive tracheal, laryngeal and pulmonary afferents (Kalia & Richter 1985) and have an important role in both respiratory control and possibly rhythm generation (Euler et al 1973; Merrill 1974; Feldman et al 1985; Feldman 1986; McCrimmon et al 1987). The carotid sinus and aortic body nerves terminate in the dorsal and dorsolateral region of the solitary complex which may have an important role in cardiovascular regulation (Ciriello et al 1981; Ciriello 1983).

Spinal Trigeminal Nucleus

The vagus contains somatic afferent nerve fibres from the skin of the concha of the external ear and from the meninges of the posterior fossa and foramen magnum. These are believed to terminate in the pars caudalis of the spinal trigeminal nucleus together with visceral afferent pain fibres from the larynx (Brodal 1947).

Vagal rootlets unite to form a flat cord which passes below the flocculus to the jugular foramen, by which it leaves the cranium. As it emerges it accompanies the accessory nerve, sharing an arachnoid and dural sheath; both lie anterior to a fibrous septum which separates them from the glossopharyngeal nerve. After emerging from the foramen the vagus has two marked enlargements, the small round superior ganglion and the larger inferior ganglion.

Superior (Jugular) Ganglion

This is greyish, spherical and about 4mm in diameter in man. It is connected to the cranial root of the accessory nerve, the inferior glossopharyngeal ganglion, and to the sympathetic trunk by a filament from the superior cervical ganglion. The significance of these connections is not entirely clear but the first probably contains aberrant motor fibres from the nucleus ambiguus which issue in the accessory nerve, to be distributed to the palatal, pharyngeal, laryngeal and upper oesophageal musculature via the vagus; the sympathetic connection may be like the one between this sympathetic ganglion and the inferior vagal ganglion. As it leaves the superior ganglion the auricular branch gives off an ascending filament to the facial nerve. In cats the jugular ganglion contains about 8 700 unipolar neurons, 73% of which appear to form the auricular nerve, which is composed of heavily myelinated somatic afferents, and 15% contribute to the vagus itself (Foley & DuBois 1937). Counts are apparently not available for the human ganglion; but since the human vagus nerve contains, at midcervical level, about 16 500 (Rt) and 20 000 (Lt) myelinated fibres, counted in 17 paired nerves, it follows that human ganglionic neurons must be more numerous (Schnitzlein et al 1958).

Inferior (Nodose) Ganglion

This is larger than the superior ganglion, being elongated and cylindrical in shape with a length of about 25 mm and a maximum breadth of 5 mm. It is connected with the hypoglossal nerve, the loop between the first and second cervical spinal nerves, and with the superior cervical sympathetic ganglion. The cranial root of the accessory nerve passes over the inferior ganglion, attached only by fibrous tissue. Beyond the ganglion the cranial accessory blends with the vagus nerve, its fibres distributed mainly in pharyngeal and recurrent laryngeal vagal branches. Most visceral afferent fibres are located in the nodose ganglion; in cats it is estimated to contain about 30 000 neurons (Jones 1937; DuBois & Foley 1937), most are unipolar but a few are fusiform or bipolar; most are in the range of 35–45mm (Mohiuddin 1953).

Both vagal ganglia are exclusively sensory, containing somatic, special visceral and general visceral afferent neurons which are unipolar (Ramon y Cajal 1909; Gabella 1976). The superior ganglion is chiefly somatic, most of its neurons entering the auricular nerve, whilst neurons in the inferior ganglion are concerned with visceral sensation from the heart, larynx, lungs and alimentary tract from the pharynx to the transverse colon; some fibres transmit impulses from taste endings in the vallecula and epiglottis. In addition there are large afferent fibres derived from muscle spindles in the laryngeal muscles (Lucas Keene 1961; Grim 1967; Mei 1970). Vagal sensory neurons in the nodose ganglion may have a topographical layout (Collman et al 1992). Both ganglia are traversed by parasympathetic and perhaps some sympathetic fibres but there is no evidence that vagal parasympathetic components relay in the inferior ganglion. Preganglionic motor fibres from the dorsal vagal nucleus and the special visceral efferents from the nucleus ambiguus, which descend to the inferior vagal ganglion, commonly form a visible band, skirting the ganglion in some mammals (Hoffman & Kuntz 1957); Mei & Dussardier 1966). These larger fibres appear to provide motor innervation to the larynx in the recurrent laryngeal nerve with some contribution to the superior laryngeal nerve supplying cricothyroid.

In man the superior laryngeal nerve contains 15 000 fibres with 30% being myelinated afferents (Ogura & Lam 1953). In contrast only 3% of fibres in the recurrent laryngeal nerve appear to be afferent (Brocklehurst & Edgeworth 1940). The abdominal vagus is composed almost entirely of unmyelinated fibres (Sharma & Thomas 1975).

Course

The vagus nerve descends vertically in the neck in the carotid sheath, between the internal jugular vein and the internal carotid artery to the upper border of the thyroid cartilage and then passes between the vein and the common carotid artery to the root of the neck. Its further course differs on the two sides.

The right vagus nerve descends posterior to the internal jugular vein to cross the first part of the subclavian artery, entering the thorax and descending through the superior mediastinum, at first behind the right brachiocephalic vein, then right of the trachea and posteromedial to the right brachiocephalic vein and superior vena cava. The right pleura and lung are lateral to it above but are separated from it below by the azygos vein, which arches forwards above the right pulmonary hilum. The nerve then passes behind the right principal bronchus to the posterior aspect of the right hilum and divides into the posterior pulmonary (bronchial) branches, which unite with rami from the second to fifth or sixth thoracic sympathetic ganglia to form the right posterior pulmonary plexus. From the caudal part of this plexus two or three branches descend on the dorsal surface of the oesophagus, where, with a left vagal ramus, they form the posterior oesophageal plexus, from which a trunk is reformed and continued posterior to the oesophagus to traverse the diaphragmatic oesophageal opening. This posterior vagal trunk contains fibres from both vagus nerves.

In the abdomen the posterior vagal trunk divides into a small gastric and a larger coeliac branch. The former supplies the postero-inferior gastric surface except the pyloric canal. The coeliac branch ends chiefly in the coeliac plexus but sends twigs to the splenic, hepatic, renal, suprarenal and superior mesenteric plexuses.

The left vagus enters the thorax between the left common carotid and subclavian arteries and behind the left brachiocephalic vein. It descends through the superior mediastinum and crosses the left side of the aortic arch to pass behind the left pulmonary hilum. Above the aortic arch it is crossed anterolaterally by the left phrenic nerve and on the arch by the left superior intercostal vein. Behind the hilum it divides into the posterior pulmonary (or bronchial) branches, which unite with rami of the second to fourth thoracic sympathetic ganglia; this forms the left posterior pulmonary plexus, two branches of which descend anteriorly on the oesophagus forming, with a ramus from the right posterior pulmonary plexus, the anterior oesophageal plexus. From this a trunk containing fibres from both vagus nerves continues anterior to the oesophagus, entering the abdomen through the oesophageal diaphragmatic opening.

In the abdomen the anterior vagal trunk supplies the cardiac antrum of the stomach and then divides into right and left branches. The left group follows the lesser gastric curvature to supply the anterosuperior surface of the stomach. The right group has three main branches. The first, sometimes duplicated, proceeds between the layers of lesser omentum towards the porta hepatis, dividing into: (a) upper branches entering the porta, and (b) lower branches supplying chiefly the pyloric canal, pylorus, superior and descending parts of the duodenum and the head of the pancreas. The second is distributed to the anterosuperior surface of the body of the stomach; the third branch follows the lesser curvature to the angular notch.

Course of the Hypoglossal nerve

Hypoglossal Nerve

The hypoglossal nerve is motor to all the muscles of the tongue, except the palatoglossus. (It has been suggested that the palatoglossus is innervated from two sources, namely from the nucleus ambiguus and also from the lateral hypoglossal nucleus (Sokoloff & Deacon 1992).) The hypoglossal lies in series with the oculomotor, trochlear and abducent nerves and the ventral nerve roots of the spinal nerves and represents the fused ventral roots of probably four precervical or spino-occipital nerves whose dorsal roots have disappeared.

The Hypoglossal Nucleus

This is in line with the spinal anterior grey column. It is about 2 cm long, its rostral part corresponding with the hypoglossal triangle in the floor of the fourth ventricle, its caudal part extending into the closed part of the medulla oblongata, where it is ventral and paramedial in the central grey matter (8.128). Its fibres pass ventrally through the medulla to emerge as a linear series of 10–15 rootlets in the anteriolateral sulcus between the pyramid and olive.

The hypoglossal nucleus is organized into two main nuclear tiers, either ventral and dorsal or ventromedial and dorsolateral (according to species studied), each divisible into a medial–lateral sequence of subnuclei (Kosaka & Yagita 1903; Stuurman 1916; Barnard 1940; O'Reilly & Fitzgeralds 1990). In the hypoglossal nucleus of the cynomolgus monkey, the medial nucleus consists of a pars medialis and a pars intermedialis and the lateral nucleus contains a pars ventralis and a pars dorsalis with, in addition, cell columns constituting small ventral and ventrocaudal nuclei (Sokoloff & Deacon 1992).

There is a musculotopic organization of motor neurons within the hypoglossal nuclei which corresponds to structural and functional divisions of tongue musculature. Thus, motor neurons

innervating tongue retrusor muscles are located in dorsal or dorsolateral nuclei, whereas motor neurons innervating the main tongue protrusor muscle are located in ventral, ventromedial or intermediate regions of the nucleus (Krammer et al 1979; Uemura et al 1979; Lowe 1981). This basic pattern of musculotopic organization has been found in all mammals studied (cat, dog, monkey, rat), and is apparently conserved in non-mammalian vertebrates. Although relatively little is known about the organization of motor neurons innervating the intrinsic muscles of the tongue, a recent tract-tracing study in the cynomolgus monkey has revealed that motor neurons of the medial divisions of the hypoglossal nucleus innervate tongue muscles that are oriented in planes transverse to the long axis of the tongue (transverse and vertical intrinsics and genioglossus), whereas motor neurons of the lateral divisions innervate tongue muscles that are oriented parallel to this axis (styloglossus, hyoglossus, superior and inferior longitudinal) (Sokoloff & Deacon 1992). It is possible that the overlap of motor neuron pools innervating similarly oriented extrinsic and intrinsic muscles may facilitate the simultaneous recruitment of these muscles.

Connections and Course

The hypoglossal nucleus receives corticonuclear fibres from the precentral gyrus and adjacent areas of mainly the contralateral hemisphere, some fibres leave the tract in the pons to travel in the medial lemniscus; they connect with the nucleus directly or via internuncial neurons. Evidence indicates that the most medial subnuclei receive projections from both hemispheres. The nucleus may connect with the cerebellum via adjacent perihypoglossal nuclei (Torvik & Brodal 1954) and perhaps also with the medullary reticular formation, the trigeminal sensory nuclei and the solitary nucleus.

The hypoglossal rootlets run laterally behind the vertebral artery, collected into two bundles which perforate the dura mater separately opposite the hypoglossal (anterior condylar) canal in the occipital bone, uniting after traversing it; the canal is sometimes divided by a bony spicule. The separate dural sheaths confirm the composite character of the nerve. It emerges from its canal in a plane medial to the internal jugular vein, internal carotid artery, ninth, tenth and eleventh cranial nerves and passes inferolaterally behind the internal carotid artery and glossopharyngeal and vagus nerves to the interval between the artery and the internal jugular vein. Here it makes a half-spiral turn round the inferior vagal ganglion, being united with it by connective tissue. It then descends almost vertically between the vessels and anterior to the vagus to a point level with the mandibular angle, becoming superficial below the posterior belly of the digastric and emerging between the internal jugular vein and internal carotid artery. It loops round the inferior sternocleidomastoid branch of the occipital artery (p. 1515), crosses lateral to both internal and external carotid arteries and the loop of the lingual artery a little above the tip of the greater cornu of the hyoid and is itself crossed by the facial vein. It inclines up and forwards on the hyoglossus by passing deep to the digastric tendon, stylohyoid and the posterior border of the mylohyoid. Between the hyoglossus and mylohyoid the nerve is inferior to the deep part of the submandibular gland, submandibular duct and lingual nerve. It then passes on to the lateral aspect of the genioglossus, continuing forwards in its substance as far as the tip of the tongue and distributing fibres in the muscle.

The hypoglossal nerve communicates with the sympathetic trunk, vagus, first and second cervical nerves and lingual nerve. Near the atlas it is joined by branches from the superior cervical sympathetic ganglion and by a filament from the loop between the first and second cervical nerves which leaves the hypoglossal as the upper root of the ansa cervicalis. The vagal connections occur close to the skull, numerous filaments passing between the hypoglossal nerve and the inferior vagal ganglion in the connective tissue uniting them. As the hypoglossal nerve curves round the occipital artery it receives from the pharyngeal plexus the ramus lingualis vagi. Near the anterior border of hyoglossus it is connected with the lingual nerve by many filaments ascending on the muscle .

Branches

The branches of distribution of the hypoglossal nerve are: meningeal, descending, thyrohyoid and muscular.

The Meningeal Branch or Branches

These leave the hypoglossal nerve in its canal, returning through it to supply the diploë of the occipital bone, the dural walls of the occipital and inferior petrosal sinuses and much of the floor and anterior wall of the posterior cranial fossa. These meningeal rami may not contain hypoglossal fibres but ascending, mixed sensory and sympathetic fibres from the upper cervical nerves and superior cervical sympathetic ganglion (Kimmel 1961a, b).

The Descending Branch

(Descendens hypoglossi or upper root of the ansa cervicalis).

This leaves the hypoglossal nerve where it curves round the occipital artery and then descends anterior to or in the carotid sheath. It contains only fibres from the first cervical spinal nerve. After giving a branch to the superior belly of the omohyoid, it is joined by the lower root of the ansa from the second and third cervical spinal nerves. The two roots form the ansa cervicalis (ansa hypoglossi), from which branches supply the sternohyoid, sternothyroid and the inferior belly of the omohyoid; another branch is said to descend anterior to the vessels into the thorax to join the cardiac and **phrenic** nerves.

The Nerves to the Thyrohyoid and Geniohyoid

These arise near the posterior border of the hyoglossus and cross obliquely the greater cornu of the hyoid to supply the thyrohyoid and geniohyoid; they contain fibres of the first cervical spinal nerve. Motor neurons innervating the geniohyoid have been demonstrated (using HRP) in subnuclei of the ventral tier of the hypoglossal nuclear complex in the macaque and in the rat (Uemura et al 1979; Uemura-Sumi et al 1981; Kitamura et al 1983; O'Reilly & Fitzgerald 1990; Sokoloff & Deacon 1992).

Muscular Branches

These are distributed to the styloglossus, hyoglossus and genioglossus. Numerous slender rami ascend into the tongue to supply its intrinsic muscles; all contain true hypoglossal fibres.

Lesions of the Hypoglossal Nerve

Complete hypoglossal division causes unilateral lingual paralysis and hemiatrophy; the protruded tongue deviates to the paralysed side; on retraction, the wasted and paralysed side also rises higher than the unaffected side. The larynx may deviate towards the active side in swallowing, due to unilateral paralysis of the hyoid depressors. If paralysis is bilateral, the tongue is motionless. Taste and tactile sensibility are unaffected but articulation is slow and swallowing very difficult.

Ventral rami of the spinal nerves: Muscular branches

Muscular Branches

These supply the rectus capitis lateralis, rectus capitis anterior, longus capitis and longus colli.

Inferior Root of the Ansa Cervicalis

(Nervus descendens cervicalis).

This is formed by the union of a branch from the second with another from the third cervical ramus. It descends on the lateral side of the internal jugular vein, crosses it a little below the middle of the neck, and continues forwards to join the superior root anterior to the common carotid artery, forming the ansa cervicalis (ansa hypoglossi), from which all infrahyoid muscles are supplied, except the thyrohyoid. In 160 dissections, the inferior root was from the second and third cervical ventral rami in 74%, from the second to fourth in 14%, from the third alone in 5%, from the second alone in 4% and from the first to third in 2%.

The Phrenic Nerve

This is the sole motor supply to the diaphragm, and also contains widespread sensory fibres. It arises chiefly from the fourth cervical ramus but also has contributions from the third and fifth (8.365).

Formed at the upper part of the lateral border of the scalenus anterior, it descends almost vertically across it behind the prevertebral fascia on its anterior surface. It descends posterior to the sternocleidomastoid, the inferior belly of omohyoid (near its intermediate tendon), the internal jugular vein, transverse cervical and suprascapular arteries and, on the left, the thoracic duct. It then runs anterior to the subclavian artery, posterior to the subclavian vein and enters the thorax by crossing medially in front of the internal thoracic artery, after which it descends anterior to the pulmonary hilum, between the fibrous pericardium and mediastinal pleura, to the diaphragm, accompanied by the pericardiophrenic vessels. The right and left phrenic nerves differ in their intrathoracic relations.

The right phrenic nerve, shorter and more vertical, is separated at the root of the neck from the second part of the right subclavian artery by the scalenus anterior. It is then lateral to the right brachiocephalic vein, the superior vena cava and the fibrous pericardium covering the right surface of the right atrium and inferior vena cava.

The left phrenic nerve, at the root of the neck, is commonly stated to leave the medial edge of the scalenus anterior to pass anterior to the first part of the left subclavian artery and behind the thoracic duct. However, Qvist (1977) claims that both right and left nerves are symmetrical in their cervical course and that at the thoracic inlet the left crosses anterior to the second part of the left subclavian artery, separated by the scalenus anterior. Thereafter the left phrenic crosses anterior to the left internal thoracic artery, descending across the medial aspect of the apex of the left lung and its pleura to the first part of the subclavian artery, which it crosses obliquely to reach a groove between the left common carotid and subclavian arteries. It passes anteromedially superficial to the left vagus nerve just above the aortic arch and behind the left brachiocephalic vein. It then passes superficial to the aortic arch and the left superior intercostal vein, anterior to the left pulmonary hilum, to lie between the fibrous pericardium covering the left surface of the left ventricle and the mediastinal pleura.

In the neck each nerve receives variable filaments from the cervical sympathetic ganglia or their branches and may also connect with internal thoracic sympathetic plexuses; these connections may represent a devious course of sympathetic fibres to these plexuses. In its thoracic course each nerve supplies sensory branches to the mediastinal pleura, fibrous pericardium and parietal serous pericardium.

Diaphragmatic Relations

(Merendino et al 1956; Perera & Edwards 1957)

The right phrenic nerve traverses the central tendon of the diaphragm, either by the caval orifice or just lateral to it. The left phrenic nerve traverses the muscular part of the diaphragm anterior to the central tendon, just lateral to the left cardiac surface and more anterior than the right phrenic. At the diaphragm or slightly above it, each phrenic nerve supplies fine branches to the parietal pleura above, and the parietal peritoneum below, the central diaphragm. The trunk of each nerve then divides as it traverses the diaphragm into commonly three branches arranged as follows, with some variation:

- (1) An anterior (sternal) branch runs anteromedially towards the sternum, connecting with its fellow.
- (2) An anterolateral branch runs laterally anterior to the lateral leaf of the central tendon.

(3) A short posterior branch divides into a posterolateral ramus coursing behind the lateral leaf and a posterior (crural) ramus supplying the crural fibres; posterolateral and crural branches may arise separately from the phrenic nerve.

These main branches are often submerged in diaphragmatic muscle or below it; they supply motor fibres to the diaphragmatic muscle and sensory fibres to the peritoneum and pleura related to the central part of the diaphragm. They also contain proprioceptive fibres from the musculature. Location of the main branches is of importance in avoiding surgical damage. The right crus splits to enclose the oesophagus; the right phrenic nerve supplies the part of it to the right of the oesophagus, the left supplying the left crus and the part of the right crus on the left of the oesophagus (Collis et al 1954; Thornton & Schweisthal 1969).

On the diaphragm's inferior surface phrenic rami connect with branches of the coeliac plexuses; on the right, at the junction of the plexuses, is a small phrenic ganglion. Rami from the plexuses supply the suprarenal glands and, on the right, the hepatic falciform and coronary ligaments and the inferior vena cava and possibly (via connections with coeliac and hepatic plexuses) the gallbladder.

Accessory Phrenic Nerve

Fibres for the phrenic nerve from the fifth cervical ventral ramus often pass in a branch of the nerve to the subclavius, the accessory phrenic nerve. This lies lateral to the main nerve and descends posterior, or sometimes anterior, to the subclavian vein; it usually joins the phrenic near the first rib but may not do so until near the pulmonary hilum or beyond. An accessory phrenic nerve may be derived from the fourth or sixth cervical rami or from the ansa cervicalis.

Lesions of the Phrenic Nerve

Division of the phrenic nerve in the neck completely paralyses the corresponding half of the diaphragm, which atrophies. If an accessory phrenic nerve exists, section or crushing of the main nerve as it lies on the scalenus anterior will not produce complete paralysis. The phrenic nerve may be involved with traumatic lesions of the upper brachial plexus and this can be demonstrated by X-ray screening of the diaphragm.

Deep Branches—Lateral Series

| | | |
|-------------------------|---------------------|----------|
| Communicating—Accessory | | C2, 3, 4 |
| Muscular branches | Sternocleidomastoid | C2, 3, 4 |
| Muscular branches | Trapezius | C2, (3) |
| Muscular branches | Levator scapulae | C3, 4 |
| Muscular branches | Scalenus medius | C3, 4 |

Communicating Branches

Lateral deep branches of the cervical plexus connect with the spinal accessory nerve in the sternocleidomastoid, posterior triangle and under the trapezius.

Muscular Branches

These are distributed to sternocleidomastoid and to the trapezius, levator scapulae and scalenus medius. Trapezial branches cross the posterior triangle obliquely below the spinal accessory nerve.

Brachial plexus

Brachial Plexus

The brachial plexus is a union of the lower four cervical ventral rami and the greater part of the first thoracic ventral ramus; the fourth ramus usually gives a branch to the fifth and the first thoracic frequently receives one from the second. Contributions to the plexus by C4 and T2 vary; when the branch from C4 is large, that from T2 is frequently absent and the branch from T1 is reduced, forming a prefixed type of plexus. If the branch from C4 is small or absent, the contribution of C5 is reduced but that of T1 is larger and one from T2 is always present; this arrangement constitutes a postfixed type of plexus. These ventral rami are the roots of the plexus, almost equal in size but variable in their mode of junction. The commonest arrangement is as follows: the fifth and sixth rami unite at the lateral border of the scalenus medius as the upper trunk; the eighth cervical and first thoracic rami join behind the scalenus anterior as the lower trunk; the seventh cervical becomes the middle trunk. These three trunks incline laterally; just above or behind the clavicle each bifurcates into anterior and posterior divisions; the anterior divisions of the upper and middle trunks form a lateral cord, lateral to

the axillary artery. The anterior division of the lower trunk descends at first behind, then medial to the axillary artery, forming the medial cord which often receives a branch from the seventh cervical ramus. Posterior divisions of all three form the posterior cord, at first above and then behind the axillary artery. The posterior division of the lower trunk is much smaller than the others, containing few, if any, fibres from the first thoracic ramus. It is frequently derived from the eighth cervical before the trunk is formed. Despite the adaptation to evolutionary changes in upper-limb musculature, the human brachial plexus reflects the original flexor–extensor organization of a primitive fin. The posterior cord is the extensor supply, the medial and lateral cords the flexor supply. Migration of muscle masses has modified this pattern; e.g. brachialis and the anterior part of the deltoid are supplied (the former in part) from 'extensor' nerves. For comparative morphology of the plexus consult Harris (1939).

Relations of the Brachial Plexus

In the neck, the plexus is in the posterior triangle, in the angle between the clavicle and lower posterior border of the sternocleidomastoid, covered by platysma, deep fascia and skin, through which it is palpable. It is crossed by the supraclavicular nerves, the nerve to the subclavius, the inferior belly of the omohyoid, the external jugular vein and the superficial ramus of the transverse cervical artery (10.92). It emerges between the scaleni anterior and medius; its proximal part is superior to the third part of the subclavian artery, the lower trunk posterior to it; the plexus passes posterior to the medial two-thirds of the clavicle, the subclavius and the suprascapular vessels and lies on the first digitation of the serratus anterior and the subscapularis.

In the axilla the lateral and posterior cords are lateral to the first part of the axillary artery, the medial cord being behind it. The cords surround the second part of the artery, related according to their names. In the lower axilla the cords divide into nerves for the upper limb. Except for the median nerve's medial root, these nerves are related to the artery's third part as their cords are to the second; i.e. branches of the lateral cord are lateral, of the medial cord medial and of the posterior cord posterior, to the artery.

Close to their exit from the intervertebral foramina, the fifth and sixth cervical ventral rami receive grey rami communicantes from the middle cervical sympathetic ganglion, the seventh and eighth from the cervicothoracic ganglion. The first thoracic ventral ramus also receives a grey ramus from and contributes a white ramus to the cervicothoracic ganglion.

Branches of the brachial plexus may be described as supraclavicular and infraclavicular.

Supraclavicular Branches

These arise from roots or from trunks:

| | | |
|-------------|---------------------------------------|-------------|
| From roots | 1. Nerves to scaleni and longus colli | C5, 6, 7, 8 |
| | 2. Branch to phrenic nerve | C5 |
| | 3. Dorsal scapular nerve | C5 |
| | 4. Long thoracic nerve | C5, 6 (7) |
| From trunks | 1. Nerve to subclavius | C5, 6 |
| | 2. Suprascapular nerve | C5, 6 |

Branches to the scaleni and longus colli arise from the lower cervical ventral rami near their exit from the intervertebral foramina. Anterior to the scalenus anterior the phrenic nerve is joined by a branch from the fifth cervical ramus.

Dorsal Scapular Nerve

This comes from the fifth cervical ventral ramus, pierces the scalenus medius, passes behind the levator scapulae, which it occasionally supplies, and runs with the deep branch of the dorsal scapular artery to the rhomboids, which it supplies.

Long Thoracic Nerve

This is usually formed by roots from the fifth to the seventh cervical rami; the last may be absent. (70 dissections demonstrated all three roots in only 42%, Alexandre et al 1968.) The upper two roots pierce the scalenus medius obliquely, uniting in or lateral to it; the nerve descends dorsal to the brachial plexus and the first part of the axillary artery. Crossing the superior border of serratus anterior to reach its lateral surface, it may be joined by the root from C7, which emerges between the scaleni anterior and medius and descends on the latter's lateral surface. The nerve continues downwards to the lower border of the serratus anterior, supplying branches to each of its digitations.

Lesions of the Brachial Plexus

Lesions of the brachial plexus commonly affect either the upper part of the plexus, that is the C5 and C6 roots and the upper trunk, and these are usually traumatic; or the lower part of the brachial plexus, that is the C8 and T1 roots and the lower trunk, when lesions may be caused by trauma but may also be produced by malignant infiltration or a thoracic outlet syndrome. Severe trauma may affect the whole plexus.

Upper Plexus Palsies

Rucksack palsy is due to a traction on the upper trunk of the brachial plexus from heavy and maladjusted rucksacks. Since axonal continuity is preserved recovery is usually complete. Severe traction injuries may occur in motorcycle accidents with lateral flexion of the head away from downward displacement of the shoulder, causing a traction injury of the upper part of the brachial plexus. The whole plexus may be involved in these injuries and sometimes the nerve roots are avulsed from the cervical spinal cord. There is gross wasting and weakness of the shoulder girdle muscles (C5) with inability to abduct the arm, and with marked weakness of elbow flexion and wrist extension (C5 and 6).

Lesions of the Lower Part of the Brachial Plexus

Malignant infiltration of the brachial plexus may result from extension of an apical lung carcinoma (Pancoast tumour) or from metastatic spread, often from carcinoma of the breast. There is slowly progressive weakness usually starting in the small hand muscles (T1) and spreading to involve the finger flexors (C8). This is usually a painful condition and the pain may be severe. There is sensory loss on the medial aspect of the forearm (T1) extending into the medial side of the hand and to the little finger (C8). A Horner's syndrome may occur if there is involvement of the cervical sympathetic ganglia. A similar syndrome may occur following radiotherapy for breast carcinoma, but this is usually painless. Thoracic surgery involving a sternal split may cause traction on the brachial plexus and usually affects the lower part of the plexus.

The lower trunk of the brachial plexus (C8, T1) may be angulated over a cervical rib, together with the subclavian artery (the thoracic outlet syndrome). Patients may present with vascular symptoms due to kinking of the subclavian artery (this is more likely to occur with large bony ribs), or they may present with neurological deficit (this is more likely in patients with small rudimentary ribs which extend into a fibrous band which joins the first rib anteriorly). Cervical ribs are quite common and are rarely associated with symptoms. There is a slow insidious onset of wasting of the small hand muscles, often starting on the lateral side with involvement of the thenar eminence and first dorsal interosseous, with pain and paraesthesiae in the medial aspect of the forearm extending to the little finger, which is often aggravated by carrying shopping or suitcases. A bruit may be heard over the subclavian artery and the radial pulse may be easily obliterated by movements of the arm, particularly with the arm extended and abducted at the shoulder.

Neuralgic Amyotrophy

This is a demyelinating neuropathy which principally affects branches of the brachial plexus, so that a characteristic feature is the dense involvement of some muscles within a myotome while others in the same myotome are not affected. For example, involvement of the suprascapular nerve causes marked weakness of supraspinatus and infraspinatus, but deltoid may be normal. More rarely the median, radial or ulnar nerves may be affected and the condition may present with an anterior or occasionally a posterior interosseous nerve palsy. There is severe pain in the shoulder girdle initially and the weakness may not become evident until the pain starts to subside after a week or so. Wasting of the affected muscles then becomes evident. The weakness may take up to 18 months to recover and is sometimes permanent. Some wasting usually persists. There may be more than one branch of the brachial plexus involved, either clinically or electrophysiologically, and electromyography can confirm the dense involvement of some muscles with sparing of others in the same myotome.

Neuralgic Amyotrophy

The long thoracic nerve is the most common nerve to be affected by neuralgic amyotrophy. Winging of the scapula may be the only clinical manifestation: it is best demonstrated by asking the patient to push against resistance with the arm extended at the elbow and flexed to 90° at the shoulder.

Nerve to the Subclavius

Small and arising near the junction of the fifth and sixth cervical ventral rami, this descends anterior to the plexus and the third part of the subclavian artery and is usually connected to the **phrenic** nerve. It passes above the subclavian vein to supply the subclavius.

Suprascapular Nerve

A large branch of the superior trunk, this runs laterally deep to the trapezius and omohyoid, enters the supraspinous fossa through the suprascapular notch inferior to the superior transverse scapular ligament, runs deep to the supraspinatus and curves round the lateral border of the scapular spine with the suprascapular artery to reach the infraspinous fossa, where it gives two branches to the supraspinatus and articular rami to the shoulder and acromioclavicular joints. The suprascapular nerve was found to have a cutaneous branch in six upper limbs out of 61 Japanese cadavers (Horiguchi 1980). When present, it pierced the deltoid muscle close to the tip of the acromion; in the one case where its peripheral distribution was examined, it was found to supply the skin of the proximal third of the arm within the territory of the axillary nerve.

Lesions of the Suprascapular Nerve

The commonest cause involving the suprascapular nerve is neuralgic amyotrophy, but an entrapment neuropathy may occur in the scapular notch or the nerve may be damaged by trauma to the scapula and shoulder. There is pain in the shoulder and wasting and weakness of supraspinatus and Infraspinatus

Sympathetic nervous system

Sympathetic Nervous System

The sympathetic system includes the two ganglionated trunks and their branches, plexuses and subsidiary ganglia. It has a much wider distribution than the parasympathetic, for it innervates: all sweat glands, the arrectores pilorum, the muscular walls of many blood vessels, the heart, lungs and respiratory tree, the abdomino-pelvic viscera, the oesophagus, the muscles of the iris in the eye, and non-striated muscle of the urogenital tract, the eyelids and elsewhere.

There are differences in the pattern of sympathetic innervation of different effector tissues; for example, visceral smooth muscles such as the vas deferens and iris receive a dense varicose nerve plexus throughout with close, 20 nm neuromuscular separations, while most blood vessels receive an innervation which is confined to the adventitial–medial border with neuromuscular separations often greater than 80 nm.

Efferent Pathways

The preganglionic fibres are axons of somata in the lateral grey column of all the thoracic and the upper two or three lumbar spinal segments, where they form intermediomedial and intermediolateral neuronal groups. The axons are myelinated, with diameters of 1.5–4 mm, and emerge from the spinal cord through the ventral spinal roots, passing into the spinal nerves at the start of their ventral rami, which they soon leave in white rami communicantes, to join either the corresponding ganglia of the sympathetic trunks or their interganglionic segments. This outflow is confined to the thoracolumbar region, the white rami communicantes being restricted to these 14 pairs of spinal nerves, although a limited outflow in other spinal nerves has been suggested. Neurons like those in the lateral grey column exist at other levels of the cord above and below the thoracolumbar outflow (Mitchell 1953) and small numbers of their fibres issue in other ventral roots. Dorsal spinal roots may also contain vasodilator fibres. Reaching the sympathetic trunk, preganglionic fibres may behave in several ways: (1) They may synapse with neurons in the nearest ganglion. (2) They may traverse this, ascending or descending in the sympathetic chain to end in another ganglion; note however that preganglionic fibres do not divide into ascending and descending branches. A single preganglionic fibre may, through collateral and terminal branches, synapse with neurons in several ganglia or terminate in only one ganglion. (3) They may traverse the nearest ganglion, ascend or descend and, without synapsing, emerge in one of the medially-directed branches of the sympathetic trunk to end at synapses in the ganglia of autonomic plexuses (mainly situated in the midline, for example around the coeliac and mesenteric arteries.). Occasionally preganglionic fibres relay in ganglia situated proximal to the sympathetic trunks; these 'intermediate ganglia' are most numerous on grey rami communicantes (see below) at cervical and lower lumbar levels; they may be of microscopic size and sometimes occur in spinal ventral roots or trunks. More than one preganglionic fibre may synapse with a single postganglionic neuron (see below).

The nervi terminales may be rostral extensions of the sympathetic system, containing efferent postganglionic fibres distributed to the blood vessels and glands of the nasal cavity, although this view has been challenged (Bojsen-Møller 1975).

The sympathetic ganglia include collections of cells on the sympathetic trunks, in the autonomic plexuses and the 'intermediate' ganglia; some ganglionic cells are dispersed in the plexuses. Originally ganglia on the trunks correspond numerically to the ganglia on the dorsal spinal roots; but adjoining ganglia may fuse and in man there are rarely more than 22 or 23 and sometimes fewer. Subsidiary ganglia in the major autonomic plexuses (e.g. coeliac, superior mesenteric ganglia, etc.) are derivatives of the ganglia of the trunks. The functional properties of sympathetic ganglia have been investigated extensively over many decades, their peripheral location providing a valuable means of studying interneuronal communication, as well as other aspects of neurobiology (for reviews of the earlier literature, see p. 1292; more recent accounts are given by Gabella (1976), Eränkö (1978), Elfvin (1983) and Szurszewski and King (1989)).

Structure of Sympathetic Ganglia

The classic studies by Langley and his successors led to the view that the autonomic ganglia are relay stations, a concept largely corroborated by anatomical observation, although it was soon recognized that a minor fraction of the fibres traversed one or more ganglia without synapse, some being efferent fibres en route to another ganglion and others afferents from the viscera and glands. This concept remains substantially true but has been modified and extended by electron microscopy, neurohistochemistry and electrophysiology, for example a considerable variation in the ratio between pre- and postganglionic fibres has been found (consult Skok 1973). The superior cervical sympathetic

ganglion, the most extensively studied, has ratios varying from 1:28 to 1:176 in different mammalian species (Billingsley & Ranson 1918; Samuel 1953; Ebbesson 1968). It has long been accepted that preganglionic axons may synapse with many postganglionic neurons for the wide dissemination and perhaps amplification of sympathetic activity, a characteristic not shared to the same degree by parasympathetic ganglia. Dissemination may be achieved by:

- multiple synapses of preganglionic nerve fibres
- the mediation of interneurons
- the diffusion within the ganglion of transmitter substances locally produced (paracrine effect) or by a local response to a substance produced elsewhere (endocrine effect).

There is evidence that all of these mechanisms are involved. The connective tissue capsule of each ganglion, continuous with the epineurium of its connecting rami, also extends as septa into the ganglion, the surrounding groups of neurons and their fibres. More delicate extensions of this stroma spread amongst the cells, each of which is surrounded by a collagenous intercellular matrix containing a few fibroblasts and many small vessels including capillaries. Satellite cells (amphicytes) encapsulate the somata of ganglionic neurons and their processes. Externally this thin sheath of satellite cells has a continuous basal lamina and the two elements screen neurons from contact with the ganglionic extracellular matrix. Neurons thus have direct access only to the internal faces of satellite cells, the two being separated only by a narrow perineuronal space of 15–20 nm which is, however, linked to the extracapsular spaces by narrow channels between the satellite cells, providing possible routes for the movement of neurotransmitter and hormonal substances between the somata of neurons and the vascular compartment.

Attempts to classify the neurons of the sympathetic (and parasympathetic) ganglia, often on inadequate criteria, have entailed disagreements and confusion. Most are multipolar, with somata ranging from 25–50 μm in man; a smaller type, of about 15–20 μm , less angular in shape and present in much smaller numbers, is often clustered in groups (De Castro & Herreros 1945) and probably corresponds to 'small intensely fluorescent' (SIF) cells (see below). Multipolar neurons display much more dendritic variation; according to McLachlan (1974) they have (in guinea pigs) a mean of 13 dendrites per cell. The complexity of these dendrites, especially those ramifying in the capsular perikaryal space, is greater in human ganglion cells. Dendritic glomeruli have been observed in many ganglia. In general ultrastructure these glomeruli resemble others; clusters of small, granular vesicles, adrenergic in type, are dispersed superficially in the perikaryon and also in the dendrites, probably representing the storage of catecholamines. Ganglionic neurons receive many axodendritic synapses from preganglionic nerve fibres, the axosomatic synapses being less numerous. Each preganglionic fibre forms several synapses with several separate dendrites, providing a mechanism for the dissemination and/or amplification of neural signals. Postganglionic fibres (see below) commonly arise from the initial stem of a large dendrite and produce few or no collateral neurites.

The existence of interneurons in sympathetic ganglia has been amply confirmed (Williams 1967; Williams & Palay 1969; Libet & Owman 1974), consisting of the SIF cells identified in sympathetic ganglia in many mammals, including man (Eränkö & Härkönen 1965; Jacobowitz 1970). Small chromaffin cells also occur in sympathetic ganglia, as recognized by Köhn in 1898. Coupland (1965a) amongst other modern workers, has ascribed them to all ganglia of the sympathetic trunk and to other sites in human neonatal material. The distinction between SIF cells and chromaffin cells appears uncertain in many accounts. The supposed two types have been identified in ganglia by separate techniques (chromaffin reaction and formalin-induced fluorescence) which cannot be applied together to a single cell. In the sympathetic ganglia of rats (Santer et al 1975) SIF cells were found to be more numerous than chromaffin cells and their modes of distribution showed some differences. Both contain catecholamines, some possibly only enough to be revealed by the more sensitive formaldehyde-induced fluorescence technique (Falck-Hillarp), whereas others may have sufficient to produce a positive chromaffin reaction (Gabella 1976). Both types may be interneurons (Santer et al 1975; Gabella 1976) Greengard and Kebedian (1974) have suggested that the SIF cells release dopamine, which is then bound by dopamine receptors on ganglionic neurons causing hyperpolarization via a cyclic AMP-dependent 'second messenger' system. In the ganglia of some species, two types of SIF cell have been described (Williams et al 1975): a minority, with long processes, end near ganglionic neurons and hence can be regarded as interneurons (Type I), while the more numerous Type II cells have shorter processes ending near blood vessels. In bovine superior cervical sympathetic ganglia, 24% of SIF cells were described as Type I and 20% were so described in cats. Although the secretory granules in Type I cells may act directly on ganglionic neurons, some SIF cells, presumably Type II, may secrete into local blood vessels (Polóyni et al 1977), exerting more distant effects. The functions of SIF cells in neurotransmission in sympathetic ganglia have been reviewed by Eränkö (1978) and

Szurszewski and King (1989), and quantification of numbers, dimensions and packing density of ganglionic neurons are reported by Gabella (1976).

The axons of the principal ganglionic cells are narrow, non-myelinated postganglionic fibres, distributed to effector organs in various ways:

(1) Those from a ganglion of the sympathetic trunk may return to the spinal nerve of preganglionic origin through a grey ramus communicans, usually joining the nerve just proximal to the white ramus, to be distributed through ventral and dorsal spinal rami to blood vessels, sweat glands, hairs, etc. in their zone of supply. Segmental areas vary in extent and overlap considerably. The extent of innervation of different effector systems, for example vasomotor, sudomotor, etc., by a particular nerve may not be the same.

(2) Postganglionic fibres may pass in a medial branch of a ganglion direct to particular viscera.

(3) They may innervate adjacent blood vessels or pass along them externally to their peripheral distribution.

(4) They may ascend or descend before leaving the sympathetic trunk as (1), (2) or (3). Many fibres are distributed along arteries and ducts as plexuses to distant effectors.

Fusion of grey and white rami may also occur, for example in the thoracic region; grey rami may also contain fasciculi of thick myelinated fibres which are somatic efferents using a grey ramus to reach the prevertebral muscles (see below), for example in the cervical region. For details of rami communicantes and their variations consult Winckler (1961).

Functional Significance

Postganglionic fibres which return to the spinal nerves supply vasoconstrictor fibres to blood vessels, are secretomotor to sweat glands and motor to the arrectores pilorum in their dermatomes. Those which accompany the motor nerves to voluntary muscles are probably only vasodilatory. Most, if not all, peripheral nerves contain post-ganglionic sympathetic fibres. Those reaching the viscera are concerned with general vasoconstriction, bronchial and bronchiolar dilatation, modification of glandular secretion, pupillary dilatation, inhibition of alimentary muscle contraction, etc. A single preganglionic fibre probably synapses with the postganglionic neurons in only one effector system; hence effects such as sudomotor and vasomotor actions can be separate. This is not necessarily true of visceral afferent fibres.

Higher Autonomic Control

Peripheral autonomic activity is integrated at higher levels in the brainstem and cerebrum, including various nuclei of the brainstem reticular formation, thalamus and hypothalamus, the limbic lobe and prefrontal neocortex, together with the ascending and descending pathways which interconnect these regions (see details of these given earlier in this section). It is now recognized that central control of the cardiovascular system is exerted by a longitudinally arranged series of parallel pathways involving specific regions of the neuraxis extending from cerebral cortex to the spinal cord (Loewry & Spyer 1990).

The sympathetic trunks are two ganglionated, irregular nerve cords extending from the cranial base to the coccyx. In the neck each lies posterior to the carotid sheath and anterior to the cervical transverse processes; in the thorax each is anterior to the heads of the ribs, in the abdomen anterolateral to the lumbar vertebral bodies and in the pelvis anterior to the sacrum and medial to the anterior sacral foramina. Anterior to the coccyx the two trunks meet in the single, median, terminal ganglion impar.

Cervical sympathetic ganglia are usually reduced to three by fusion; from the cranial pole of the superior ganglion issues the internal carotid nerve, as a continuation of the sympathetic trunk, accompanying the internal carotid artery through its canal into the cranial cavity. There are from 10–12 (usually 11) thoracic ganglia, four lumbar and four or five in the sacral region.

Cranial Part of the Sympathetic System

This begins on each side as the internal carotid nerve, a branch of the superior cervical ganglion containing the postganglionic fibres of its neurons. Ascending behind the internal carotid artery it divides in the carotid canal into branches, one medial and the others lateral to the artery. The larger, lateral branch gives filaments to the internal carotid and forms the lateral part of the internal carotid plexus; the medial branch also gives filaments to the artery and, continuing on, forms the medial part of the internal carotid plexus.

Internal Carotid Plexus

This surrounds its artery and occasionally contains a small, medial carotid ganglion; elsewhere it has some scattered postganglionic neurons. Laterally the plexus communicates with the trigeminal and pterygopalatine ganglia, the abducent nerve and tympanic branch of the glossopharyngeal; it also distributes filaments to the wall of the internal carotid artery. One or two filaments join the abducent nerve as it lies on the lateral side of the internal carotid artery. The branch to the pterygopalatine ganglion is the deep petrosal nerve, which perforates the cartilage filling the foramen lacerum and forms with the greater petrosal nerve the nerve of the pterygoid canal, traversing the canal to the pterygopalatine ganglion. The communication with the tympanic branch of the glossopharyngeal nerve is effected by the superior and inferior caroticotympanic nerves in the posterior wall of the carotid canal.

The medial part of the internal carotid plexus is inferomedial to the part of the internal carotid artery which indents the cavernous sinus lateral to the sella turcica; it gives branches to the artery and to the oculomotor, trochlear, ophthalmic and abducent nerves and the ciliary ganglion. It also sends vasomotor rami along branches of the internal carotid to the hypophysis cerebri.

The branch to the oculomotor nerve joins the nerve near its point of division and the branch to the trochlear joins it in the lateral wall of the cavernous sinus; filaments also connect with the medial side of the ophthalmic nerve and with the abducent. The filament to the ciliary ganglion, from the anterior part of the plexus, enters the orbit via the superior orbital fissure; this ramus may join the ciliary ganglion directly or unite with the communicating branch from the nasociliary nerve; or it may travel in the ophthalmic nerve and its nasociliary branch. Its fibres traverse the ganglion without synapsing and enter the short ciliary nerves to be distributed to the blood vessels of the eyeball. Fibres supplying the dilator pupillae usually travel via the ophthalmic, nasociliary and long ciliary nerves but occasionally via the short ciliary. Some fibres may also innervate the ciliaris muscle. The preganglionic fibres concerned leave the spinal cord predominantly in T1, pass to and through the cervicothoracic ganglion and ascend in the cervical sympathetic trunk to relay in the superior cervical ganglion.

The internal carotid plexus is prolonged around the anterior and middle cerebral arteries and the ophthalmic arteries, reaching the pia mater along the cerebral vessels; along the ophthalmic artery they pass into the orbit where the plexus accompanies each branch of that vessel. Filaments on the anterior communicating artery connect the sympathetic nerves of the right and left sides and may be associated with a small ganglion. Much of this detail depends on rather old observations; continued disagreement and discrepancy have been reviewed by Mitchell (1953) and Purves (1972). Electron microscopy shows that the sympathetic innervation of the cerebral arterial tree is like that of other vascular systems and the terminals of this rich perivascular plexus have been shown histochemically and immunohistochemically to contain NA and NPY in various mammals, including man (Iwayama 1970; Matsuyama et al 1985). The sources of these sympathetic vasoconstrictor nerve fibres are the internal carotid and vertebral plexuses. It should be noted that, in cerebral vessels, some NPY-containing fibres are of parasympathetic origin, and also contain ACh and VIP (Leblanc et al 1987; Uddman & Edvinsson 1989). NA-containing nerves present in some cerebral vessels after sympathectomy may be of central origin (Edvinsson 1991).

Cervical Part of the Sympathetic System

The cervical part of each sympathetic trunk contains three interconnected ganglia, the superior, middle and cervicothoracic (8.397), which send grey rami communicantes to all the cervical spinal nerves but receive no white rami communicantes from them; their spinal preganglionic fibres emerge in the white rami communicantes of the upper thoracic spinal nerves which enter the corresponding thoracic sympathetic ganglia, through which they ascend into the neck. In their course, the grey rami communicantes may pierce the longus capitis or the scalenus anterior. For details of the cervical grey rami see Potts (1925), Pick and Sheehan (1946), Sunderland and Bedbrook (1949).

Superior Cervical Ganglion

This is the largest of the three, adjoins the second and third cervical vertebrae and is probably formed from four fused ganglia corresponding to C1–4. Anterior to it is the internal carotid artery and sheath, while posterior to it is the longus capitis. The internal carotid nerve (see above) ascends from it into the cranial cavity; the lower end of the ganglion is united by a connecting trunk to the middle cervical ganglion. Its branches consist of lateral, medial and anterior groups.

The lateral branches are the grey rami communicantes to the upper four cervical spinal nerves and to some of the cranial nerves; delicate filaments pass to the inferior vagal ganglion and to the hypoglossal nerve; a branch, the jugular nerve, ascends to the cranial base and divides into two, one part joining the inferior glossopharyngeal ganglion and the other the superior vagal ganglion; other

twigs pass to the superior jugular bulb and associated jugular glomus or glomera and some to the meninges in the posterior cranial fossa.

The medial branches of the superior cervical ganglion are the laryngopharyngeal and cardiac. The laryngopharyngeal branches supply the carotid body and pass to the side of the pharynx, joining glossopharyngeal and vagal rami to form the pharyngeal plexus. A cardiac branch arises by two or more filaments from the lower part of the superior cervical ganglion, occasionally receiving a twig from the trunk between the superior and middle cervical ganglia. It is thought to contain only efferent fibres, the preganglionic outflow being from the upper thoracic segments of the spinal cord, and to be devoid of pain fibres from the heart. It descends behind the common carotid artery, in front of the longus colli, crossing anterior to the inferior thyroid artery and recurrent laryngeal nerve. The courses on the two sides then differ. The right cardiac branch usually passes behind or sometimes in front of the subclavian artery and posterolateral to the brachiocephalic trunk to the back of the aortic arch where it joins the deep (dorsal) part of the cardiac plexus. It has other sympathetic connections: about midneck it receives filaments from the external laryngeal nerve; inferiorly, one or two vagal cardiac branches join it; as it enters the thorax it is joined by a filament from the recurrent laryngeal nerve. Filaments from the nerve also communicate with the thyroid branches of the middle cervical ganglion. The left cardiac branch, in the thorax, is anterior to the left common carotid artery and crosses in front of the left side of the aortic arch to reach the superficial (ventral) part of the cardiac plexus. Sometimes it descends on the right of the aorta to end in the deep (dorsal) part of the cardiac plexus. It communicates with the cardiac branches of the middle cervical and cervicothoracic sympathetic ganglia and sometimes with the inferior cervical cardiac branches of the left vagus; branches from these mixed nerves form a plexus on the ascending aorta.

The anterior branches of the superior cervical ganglion ramify on the common and external carotid arteries and the branches of the latter, forming a delicate plexus around each in which small ganglia are occasionally found. The plexus around the facial artery supplies a filament to the submandibular ganglion; the plexus on the middle meningeal artery sends one ramus to the otic ganglion and another, the external petrosal nerve, to the facial ganglion. Many of the fibres coursing along the external carotid and its branches ultimately leave them to travel to facial sweat glands via trigeminal nerve branches.

Middle Cervical Ganglion

This is the smallest of the three. It is occasionally absent and may then be replaced by minute ganglia in the sympathetic trunk or may be fused with the superior ganglion. It is usually found at the sixth cervical vertebral level, anterior or just superior to the inferior thyroid artery, or it may adjoin the cervicothoracic ganglion (see below); it is probably a coalescence of the ganglia of the fifth and sixth cervical segments, judging by its postganglionic rami, which join the fifth and sixth cervical spinal nerves but sometimes also the fourth and seventh. The ganglion also has thyroid and cardiac branches. It is connected to the cervicothoracic ganglion by two or more very variable cords: the posterior usually splits to enclose the vertebral artery; the anterior loops down anterior to and then below the first part of the subclavian artery, medial to the origin of its internal thoracic branch, and supplies rami to it. This loop is the ansa subclavia; it is frequently multiple, lies closely in contact with the cervical pleura and generally connects with the **phrenic** nerve. Similar connections with the vagus nerve are of uncertain significance.

Thyroid branches accompany the inferior thyroid artery to the thyroid gland, communicating with the superior cardiac, external laryngeal and recurrent laryngeal nerves, and send branches to the parathyroid glands. Fibres to both glands are in part vasomotor but some reach the secretory cells (Raybuck 1952).

The cardiac branch, the largest sympathetic cardiac nerve, either arises from the ganglion itself or more often from the sympathetic trunk cranial or caudal to it. On the right side it descends behind the common carotid artery, in front of or behind the subclavian, to the trachea where it receives a few filaments from the recurrent laryngeal nerve before joining the right half of the deep (dorsal) part of the cardiac plexus. In the neck, it connects with the superior cardiac and recurrent laryngeal nerves. On the left side the cardiac nerve enters the thorax between the left common carotid and subclavian arteries to join the left half of the deep (dorsal) part of the cardiac plexus. Fine branches from the middle cervical ganglion also pass to the trachea and oesophagus.

Cervicothoracic (Stellate) Ganglion

This is irregular in shape and much larger than the middle cervical ganglion. It is probably formed by a fusion of the lower two cervical and first thoracic segmental ganglia, sometimes including the second and even third and fourth thoracic ganglia. The first thoracic ganglion may be separate, leaving an

inferior cervical ganglion above it. The sympathetic trunk turns backwards at the junction of the neck and thorax and so the long axis of the cervicothoracic ganglion becomes almost anteroposterior. The ganglion lies on or just lateral to the lateral border of the longus colli between the base of the seventh cervical transverse process and the neck of the first rib (which are posterior to it), the vertebral vessels being anterior. Below it is separated from the posterior aspect of the cervical pleura by the suprapleural membrane; the costocervical trunk branches near its lower pole. Lateral is the superior intercostal artery.

A small vertebral ganglion may be present on the sympathetic trunk anterior or anteromedial to the origin of the vertebral artery and directly above the subclavian. When present, it may provide the ansa subclavia and is also joined to the cervicothoracic ganglion by fibres enclosing the vertebral artery. It is usually regarded as a detached part of the middle cervical or cervicothoracic ganglion. Like the middle cervical ganglion it may supply grey rami communicantes to the fourth and fifth cervical spinal nerves. The cervicothoracic ganglion sends grey rami communicantes to the seventh and eighth cervical and first thoracic spinal nerves and gives off a cardiac branch, branches to nearby vessels and sometimes a branch to the vagus nerve.

The grey rami communicantes to the seventh cervical spinal nerve vary from one to five. A third often ascends medial to the vertebral artery in front of the seventh cervical transverse process, connects with the seventh cervical nerve and sends a filament upwards through the sixth cervical transverse foramen in company with the vertebral vessels to join the sixth cervical spinal nerve as it emerges from the intervertebral foramen. An inconstant ramus may traverse the seventh cervical transverse foramen. Grey rami to the eighth cervical spinal nerve vary from three to six in number.

The cardiac branch descends behind the subclavian artery and along the front of the trachea to the deep cardiac plexus. Behind the artery it connects with the recurrent laryngeal nerve and the cardiac branch of the middle cervical ganglion, the latter often being replaced by fine branches of the cervicothoracic ganglion and ansa subclavia.

Branches to blood vessels form plexuses on the subclavian artery and its branches. The subclavian supply is derived from the cervicothoracic ganglion and ansa subclavia, extending to the first part of the axillary artery; a few fibres may extend further. According to Pearson and Sauter an extension of the subclavian plexus to the internal thoracic artery is joined by a branch of the **phrenic** nerve. The vertebral plexus is derived mainly from a large branch of the cervicothoracic ganglion which ascends behind the vertebral artery to the sixth transverse foramen, reinforced by branches of the vertebral ganglion or the cervical sympathetic trunk which pass cranially on the ventral aspect of the artery; from this plexus deep rami communicantes join the ventral rami of the upper five or six cervical spinal nerves. The plexus contains some neuronal cell bodies and continues into the skull along the vertebral and basilar arteries and their branches as far as the posterior cerebral artery, where it meets a plexus from the internal carotid. Some consider the vertebral plexus to be the main intracranial extension of the sympathetic system (Lazorthes 1949; Mitchell 1952). The plexus on the inferior thyroid artery reaches the thyroid gland, connecting with recurrent and external laryngeal nerves, the cardiac branch of the superior cervical ganglion, and the common carotid plexus.

The preganglionic fibres for the head and neck emerge from the spinal cord in the upper five thoracic spinal nerves (mainly the upper three), ascending in the sympathetic trunk to synapse in the cervical ganglia. The preganglionic fibres supplying the upper limb stem from upper thoracic segments, probably T2–6 (or 7), ascending via the sympathetic trunk to synapse mainly in its cervicothoracic ganglion, whence postganglionic fibres pass to the brachial plexus (mainly its lower trunk). Most of the vasoconstrictor fibres for the upper limb emerge in the second and third thoracic ventral roots; the arteries can thus be denervated by cutting the sympathetic trunk below the third thoracic ganglion, severing the rami communicantes connected with the second and third thoracic ganglia or by cutting the ventral roots of the second and third thoracic spinal nerves (intradurally). The white ramus to the cervicothoracic ganglion is not cut, partly because it does not convey many vasomotor or sudomotor fibres to the upper limb but mainly because it contains most of the preganglionic fibres for the head and neck; these ascend the trunk to the superior cervical ganglion, from which postganglionic branches supply vasoconstrictor and sudomotor nerves to the face and neck, secretory fibres to the salivary glands, dilator pupillae (and probably ciliaris oculi), non-striated muscle in the eyelids and the orbitalis. Destruction of this nerve would thus lead to meiosis, ptosis, enophthalmos and loss of sweating on the face and neck (Horner's syndrome) and possibly some disturbance of accommodation. For a review consult Haxton (1954) and Bannister and Matthias (1992).

Blood vessels of the upper limb beyond the first part of the axillary artery receive their sympathetic supply via branches of the brachial plexus adjacent to them, e.g. the median nerve supplies branches to the brachial artery and palmar arches, the ulnar nerve supplies the ulnar artery and palmar arches and the radial nerve supplies the radial artery.

The first and second (and occasionally the third) intercostal nerves may be interconnected anterior to the necks of the ribs by filaments containing postganglionic fibres from their grey rami; these fibres provide another path by which postganglionic nerves can pass from the upper thoracic ganglia to the brachial plexus.

Thoracic Part of the Sympathetic System

The thoracic sympathetic trunk contains ganglia almost equal in number to those of the thoracic spinal nerves (11 in more than 70%, occasionally 12, rarely 10 or 13). The first thoracic ganglion is usually fused with the inferior cervical, forming the cervicothoracic ganglion; Jit and Mukerjee (1960) found a fused ganglion in 80 out of 100 dissections. Rarely the middle cervical or second thoracic ganglion may be included. The succeeding ganglion is counted as the second in order to make the other ganglia correspond numerically with other segmental structures. Except for the lowest two or three, the thoracic ganglia lie against the costal heads, posterior to the costal pleura; the lowest two or three are lateral to the bodies of the corresponding vertebrae. Caudally, the thoracic sympathetic trunk passes dorsal to the medial arcuate ligament (or through the crus of the diaphragm) to become the lumbar sympathetic trunk. The ganglia are small and interconnected by intervening segments of the trunk. Two or more rami communicantes, white and grey, connect each ganglion with its corresponding spinal nerve, white rami joining the nerve distal to the grey. Sometimes a grey and a white ramus fuse to form a 'mixed' ramus.

The medial branches from the upper five ganglia are very small, supplying filaments to the thoracic aorta and its branches. On the aorta they form a fine thoracic aortic plexus with filaments from the greater splanchnic nerve. Rami of the second to fifth or sixth ganglia enter the posterior pulmonary plexus; others, from the second to fifth ganglia, pass to the deep (dorsal) part of the cardiac plexus. Small branches of these pulmonary and cardiac nerves pass to the oesophagus and trachea. The medial branches from the lower seven ganglia are large, supplying the aorta and uniting to form the greater, lesser and lowest splanchnic nerves, the last not always being identifiable.

The greater splanchnic nerve, consisting mainly of myelinated preganglionic efferent and visceral afferent fibres, is formed by branches from the fifth to ninth or tenth thoracic ganglia; but fibres in the upper branches may be traced to the first or second thoracic ganglion. Its roots vary from one to eight, four being the most usual number. It descends obliquely on the vertebral bodies, supplies branches to the descending thoracic aorta and perforates the ipsilateral crus of the diaphragm to end mainly in the coeliac ganglion but partly in the aorticorenal ganglion and suprarenal gland. A splanchnic ganglion exists on the nerve opposite the eleventh or twelfth thoracic vertebra in 17–68% of dissections (Jit & Mukerjee 1960); but Mitchell (1953) reported microscopic evidence that it is always present.

The lesser splanchnic nerve, formed by rami of the ninth and tenth (sometimes the tenth and eleventh) thoracic ganglia and the trunk between them, pierces the diaphragm with the greater splanchnic to join the aorticorenal ganglion.

The lowest (least) splanchnic nerve (or renal nerve) from the lowest thoracic ganglion enters the abdomen with the sympathetic trunk to end in the renal plexus.

Jit and Mukerjee (1960) described in great detail dissections of the thoracic sympathetic nerves in 50 cadavers and surveyed the previous findings. The incidence of the splanchnic nerves, according to seven observers, is as follows: greater—always present, lesser—94% (86–100%), least—56% (16–98%). A fourth (accessory) splanchnic nerve has been described by de Sousa (1955) but has not been confirmed.

Lumbar Part of the Sympathetic System

The lumbar part of each sympathetic trunk, usually containing four interconnected ganglia, runs in the extra-peritoneal connective tissue anterior to the vertebral column and along the medial margin of the psoas major. Superiorly it is continuous with the thoracic trunk posterior to the medial arcuate ligament; inferiorly, passing posterior to the common iliac artery, it becomes the pelvic trunk. On the right side it is overlapped by the inferior vena cava and on the left by the lateral aortic lymph nodes. It is anterior to most of the lumbar vessels but may pass behind some lumbar veins.

The first, second and sometimes third lumbar ventral spinal rami send white rami communicantes to the corresponding ganglia. Grey rami communicantes, passing from all ganglia to the lumbar spinal nerves, are long and accompany the lumbar arteries round the sides of the vertebral bodies, medial to the fibrous arches to which the psoas major is attached.

Usually four lumbar splanchnic nerves pass from the ganglia to join the coeliac, intermesenteric (abdominal aortic) and superior hypogastric plexuses. The first lumbar splanchnic nerve, from the first ganglion, joins the coeliac, renal and intermesenteric plexuses. The second nerve, from the second and sometimes the third ganglion, joins the inferior part of the intermesenteric plexus; the third nerve

issues from the third or fourth ganglion, passing anterior to the common iliac vessels to join the superior hypogastric plexus. The fourth lumbar splanchnic, from the lowest ganglion, passes dorsal to the common iliac vessels to join the lower part of the superior hypogastric plexus or the hypogastric 'nerve'.

Vascular branches from all lumbar ganglia join the intermesenteric (aortic) plexus. Fibres of the lower lumbar splanchnic nerves pass to the common iliac arteries, forming a plexus continued along the internal and external iliac arteries as far as the proximal part of the femoral artery. Many postganglionic fibres in the grey rami, connecting the lumbar ganglia to the spinal nerves, travel in the femoral nerve to its muscular, cutaneous and saphenous branches, supplying vasoconstrictor nerves to the femoral artery and its branches in the thigh. Other postganglionic fibres travel via the obturator nerve to the obturator artery. Considerable uncertainties persist regarding sympathetic supplies to the lower limb (Wilde 1951; Wyburn 1956; Pick 1970).

Pelvic Part of the Sympathetic System

The pelvic sympathetic trunk lies in the extraperitoneal tissue anterior to the sacrum, medial or anterior to the anterior sacral foramina, and has four or five interconnected ganglia. Above, it continues into the lumbar trunk; below, the two trunks converge to unite in the small ganglion impar anterior to the coccyx. Grey rami communicantes pass from the ganglia to sacral and coccygeal spinal nerves but white rami communicantes are absent. Medial branches of distribution connect across the midline; twigs from the first two ganglia join the inferior hypogastric plexus (pelvic plexus) or the hypogastric 'nerve'; others form a plexus on the median sacral artery. The glomus coccygeum is supplied from the loop between the two trunks. The hypogastric 'nerve', which is usually plexiform, is a redundant term for the right and left connections, between the superior and inferior hypogastric plexuses.

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Vascular Branches

Through the grey rami many postganglionic fibres pass to the roots of the sacral plexus, especially those forming the tibial nerve, to be conveyed to the popliteal artery and its branches in the leg and foot. Others are carried in the pudendal and superior and inferior gluteal nerves to the accompanying arteries. Branches to lymph nodes are also described (Wozniak 1966).

Preganglionic fibres for the lower limb are derived from the lower three thoracic and upper two or three lumbar spinal segments. They reach the lower thoracic and upper lumbar ganglia through white rami; some descend through the sympathetic trunk to synapse in the lumbar ganglia, whence postganglionic fibres join the femoral nerve to supply the femoral artery and its branches; other fibres descend to synapse in the upper two or three sacral ganglia, from which postganglionic axons join the tibial nerve to supply the popliteal artery and its branches in the leg and foot. Sympathetic denervation of vessels in the lower limb can thus be effected by removing the upper three lumbar ganglia and the intervening parts of the sympathetic trunk, all the preganglionic fibres to the lower limb thus being divided.

Segmental Sympathetic Supplies

Segmental sympathetic supplies are as follows:

| | |
|------------------------------------|--------|
| Head and neck | T1–5 |
| Upper limb | T2–5 |
| Lower limb | T10–L2 |
| Heart | T1–5 |
| Bronchi and lung | T2–4 |
| Oesophagus (caudal part) | T5–6 |
| Stomach | T6–10 |
| Small intestine | T9–10 |
| Large intestine to splenic flexure | T11–L1 |

| | |
|---|--------|
| Splenic flexure to rectum | L1–2 |
| Liver and gallbladder | T7–9 |
| Spleen | T6–10 |
| Pancreas | T6–10 |
| Kidney | T10–L1 |
| Ureter | T11–L2 |
| Suprarenal | T8–L1 |
| Testis and ovary | T10–11 |
| Epididymis, ductus deferens, seminal vesicles | T11–12 |
| Urinary bladder | T11–L2 |
| Prostate and prostatic urethra | T11–L1 |
| Uterus | T12–L1 |
| Uterine tube | T10–L1 |

Plexuses in the Thoracic, Abdominal and Pelvic Cavities

The larger autonomic plexuses are aggregations of nerves and ganglia situated in the thoracic, abdominal and pelvic cavities. They are the cardiac, pulmonary, coeliac and hypogastric plexuses, supplying the thoracic, abdominal and pelvic viscera, respectively. Extensions of these major plexuses pass along most branches of the large vessels which they surround and are usually named after the artery along which they are distributed. This leads to a plethora of named plexuses, often separately described in detail which may overshadow their essential continuity.

Cardiac Plexuses

The cardiac plexus at the base of the heart is divided into superficial (ventral) and deep (dorsal) parts which are closely connected. Several small ganglia lie within it, the most constant being the cardiac ganglion described below. Mizeres (1963) has emphasized the unity of the cardiac plexus, considering its division into two parts as an artefact of dissection; he was, however, prepared to allow regional names for its coronary, pulmonary, atrial and aortic extensions. Since major concentrations of the plexus are situated as described here, the terms superficial and deep have been retained.

Superficial (Ventral) Part of the Cardiac Plexus

This lies below the aortic arch and anterior to the right pulmonary artery. It is formed by the cardiac branch of the left superior cervical sympathetic ganglion and the lower of the two cervical cardiac branches of the left vagus. A small cardiac ganglion is usually present in this plexus immediately below the aortic arch, to the right of the ligamentum arteriosum. This part of the cardiac plexus connects with (1) the deep part, (2) the right coronary plexus, (3) the left anterior pulmonary plexus.

Deep (Dorsal) Part of the Cardiac Plexus

This is anterior to the tracheal bifurcation, above the point of division of the pulmonary trunk and posterior to the aortic arch. It is formed by the cardiac branches of the cervical and upper thoracic sympathetic ganglia and of the vagus and recurrent laryngeal nerves. The only cardiac nerves which do not join it are those joining the superficial part of the plexus.

Branches from the right half of the deep part of the cardiac plexus pass in front of and behind the right pulmonary artery; those anterior to it, the more numerous, supply a few filaments to the right anterior pulmonary plexus and continue on to form part of the right coronary plexus; those behind the pulmonary artery supply a few filaments to the right atrium and then continue into the left coronary plexus. The left half of the deep part of the cardiac plexus is connected with the superficial, supplying filaments to the left atrium and left anterior pulmonary plexus and then continuing to form much of the left coronary plexus.

Left Coronary Plexus

This is larger than the right, and is formed chiefly by the prolongation of the left half of the deep part of the cardiac plexus and a few fibres from the right; it accompanies the left coronary artery to supply the left atrium and ventricle.

Right Coronary Plexus

This is formed from both superficial and deep parts of the cardiac plexus, and accompanies the right coronary artery to supply the right atrium and ventricle.

Atrial Plexuses

Described by Mizeres (1963), these are derivatives of the right and left continuations of the cardiac plexus along the coronary arteries. Their fibres are distributed to the corresponding atria, overlapping those from the coronary plexuses.

All the cardiac branches of the vagus and sympathetic contain both afferent and efferent fibres, except the cardiac branch of the superior cervical sympathetic ganglion, which is purely efferent. The efferent preganglionic cardiac sympathetic fibres arise in the upper four or five thoracic spinal segments; they pass by white rami communicantes to synapse in the upper thoracic sympathetic ganglia, though many ascend to synapse in the cervical ganglia. Postganglionic fibres from the thoracic and cervical ganglia form the sympathetic cardiac nerves, which accelerate the heart and dilate the coronary arteries. Of the sympathetic fibres from the first four or five thoracic spinal segments, the upper pass to the ascending aorta, pulmonary trunk and ventricles, the lower to the atria.

The efferent cardiac parasympathetic fibres from the dorsal vagal nucleus and neurons near the nucleus ambiguus run in vagal cardiac branches to synapse in the cardiac plexuses and atrial walls. These vagal fibres slow the heart and cause constriction of the coronary arteries. In man (like most mammals) intrinsic cardiac neurons are limited to the atria and interatrial septum (Davies et al 1952; King & Coakley 1958); they are most numerous in the subepicardial connective tissue (10.59) near the SA and AV nodes. There is now evidence that these intrinsic ganglia are not simple nicotinic relays but may act as sites for integration of extrinsic nervous inputs and form complex circuits for the local neuronal control of the heart and perhaps even local reflexes (consult Saffrey et al 1992).

Pulmonary Plexuses

These are anterior and posterior to the other hilar structures of the lungs, the anterior plexus being much smaller. According to Mizeres (1963) they are extensions from the cardiac plexus along the right and left pulmonary arteries. They are formed by vagal and sympathetic branches. Efferent parasympathetic fibres arise from the dorsal vagal nucleus; efferent sympathetic fibres are postganglionic branches of the second to fifth thoracic sympathetic ganglia.

The anterior pulmonary plexus is formed by rami from vagal and cervical sympathetic cardiac nerves as well as direct branches from both sources; the posterior pulmonary plexus is formed by the rami of vagal cardiac branches from the second to fifth or sixth thoracic sympathetic ganglia, the left plexus also receiving branches from the left recurrent laryngeal nerve. The two plexuses are interconnected; from them nerves enter the lung as networks along branches of the bronchi and pulmonary and bronchial vessels extending as far as the visceral pleura. There are small ganglia within the tracheobronchial tree of the airways with which efferent vagal preganglionic fibres synapse (Coburn 1987). They may act as sites of integration and/or modulation of the input from extrinsic nerves or permit some local control of aspects of airway function by local reflex mechanisms (Allen & Burnstock 1990). In the small intestine interstitial cells have been described in terminal autonomic networks, but have not been seen in thoracic organs, apart perhaps from the oesophagus (Dijkstra 1969). Efferent vagal fibres are bronchoconstrictor, secretomotor to bronchial glands and vasodilator. Efferent sympathetic fibres are bronchodilator and vasoconstrictor.

Coeliac Plexus

The coeliac, the largest major autonomic plexus, sited at the level of the last thoracic and first lumbar vertebrae, is a dense network uniting two large coeliac ganglia. It surrounds the coeliac artery and the root of the superior mesenteric artery. It is posterior to the stomach and omental bursa, anterior to the crura of the diaphragm and the commencement of the abdominal aorta and between the suprarenal glands. The plexus and ganglia are joined by the greater and lesser splanchnic nerves of both sides and branches from both the vagus and **phrenic** nerves. They extend as numerous secondary plexuses along adjacent arteries.

The coeliac ganglia are irregular masses, one on each side, between the suprarenal gland and the coeliac trunk and in front of the crura; the right one is behind the inferior vena cava, the left behind the splenic vessels. The upper part of each is joined by a greater splanchnic nerve; the lower part, more or less detached as the aorticorenal ganglion, receives the lesser splanchnic nerve and forms most of the renal plexus; its position is variable but near the origin of the renal artery from the aorta. (For details consult Norvell 1968). Secondary plexuses from or connected with the coeliac are: the **phrenic**, splenic, hepatic, left gastric, intermesenteric, suprarenal, renal, testicular or ovarian, superior mesenteric and inferior mesenteric.

Phrenic Plexus

This accompanies the inferior **phrenic** artery to the diaphragm, with branches to the suprarenal gland. It arises near the upper end of the coeliac ganglion and is larger on the right. It receives one or two **phrenic** branches. At the junction of the right **phrenic** plexus with the **phrenic** nerve is a small **phrenic** ganglion, distributing branches to the inferior vena cava, suprarenal and hepatic plexuses.

Hepatic Plexus

The largest coeliac derivative, this also receives filaments from the left and right vagi and right **phrenic** nerve. It accompanies the hepatic artery and portal vein and their branches into the liver, where its fibres are confined to the vicinity of the blood vessels. It follows all branches of the hepatic artery. Branches to the gallbladder form a thin cystic plexus; bile ducts are also supplied. Branches accompanying the right gastric artery supply the pylorus. From the gastroduodenal extension of the plexus branches reach the pylorus and the first part of the duodenum. Many follow the right gastro-epiploic artery to supply the right side of the stomach and the greater curvature. The superior pancreaticoduodenal extension of the plexus supplies the descending part of the duodenum, the pancreatic head and the lower part of the bile duct. The hepatic plexus contains afferent and efferent sympathetic and parasympathetic fibres; the vagal constituents are said to be motor to the musculature of the gallbladder and bile ducts and inhibitory to the sphincter of the bile duct. Petkov (1968) identified a distinct nerve to the sphincter in 23 out of 25 human dissections.

Left Gastric Plexus

This accompanies its artery along the lesser curvature of the stomach, joining with the vagal gastric branches. Gastric sympathetic nerves are motor to the pyloric sphincter but inhibitory to the gastric mural musculature.

Splenic Plexus

This is formed by branches of the coeliac plexus, left coeliac ganglion and right vagus, and accompanies its artery to the spleen, giving off subsidiary plexuses along arterial branches. The fibres are mainly, perhaps wholly, sympathetic and terminate in blood vessels and non-striated muscle of the splenic capsule and trabeculae.

Suprarenal Plexus

This is formed by branches from the coeliac ganglion and plexus and greater splanchnic nerve. Relative to its size, the suprarenal gland has a larger autonomic supply than any other organ. Its fibres are commonly described as myelinated and preganglionic. In rats, however, non-myelinated fibres are ten times as numerous and are considered preganglionic; they end in synapses, often deeply invaginated, with large chromaffin cells, the phaeochromocytes, which are thus homologous with the postganglionic sympathetic neurons. A space of 150–200 nm separates the synaptic membranes, which often have electron-dense zones. Small and large vesicles with electron-dense granular contents occur in these endings. Only non-myelinated fibres appear to innervate chromaffin cells, all of which are related to one or more such terminals. Multi-polar neurons also occur in the adrenal medulla; some preganglionic non-myelinated fibres form axodendritic synapses with them. The destination of their axons is not known (Coupland 1965a). A preponderance of non-myelinated fibres has also been described in the human suprarenal plexus (Coupland 1965a, b; Grottel 1968).

Renal Plexus

This is dense and formed by rami from the coeliac ganglion and plexus, aorticorenal ganglion, lowest thoracic splanchnic nerve, first lumbar splanchnic nerve and aortic plexus. Small ganglia occur in the renal plexus, the largest usually behind the start of the renal artery. The plexus continues into the kidney around the arterial branches to supply the vessels, renal glomeruli, and tubules, especially the cortical tubules (Norvell 1968). Renal nerves are mostly vasomotor. From the renal plexus branches supply ureteric and testicular (or ovarian) plexuses. The ureteric plexus receives, in its upper part, branches from the renal and aortic plexuses, in its intermediate part from the superior hypogastric plexus and hypogastric nerve and in its lower part from the hypogastric nerve and inferior hypogastric plexus. This supply influences the inherent motility of the ureter.

Testicular Plexus

This accompanies the testicular artery to the testis. Its upper part receives branches from the renal and aortic plexuses. Distally it is reinforced from the superior and inferior hypogastric plexuses. Its rami pass to the epididymis and ductus deferens.

Ovarian Plexus

This accompanies the ovarian artery to the ovary and uterine tube. The upper part is formed by branches from the renal and aortic plexuses; its lower part is reinforced from the superior and inferior hypogastric plexuses.

The nerves in the testicular and ovarian plexuses contain efferent and afferent sympathetic fibres; the efferents are vasomotor and derived from the tenth and eleventh thoracic spinal segments; the parasympathetic fibres, from the inferior hypogastric plexuses, are probably vasodilator.

Superior Mesenteric Plexus

This is a downward continuation of the coeliac, which receives a branch from the junction of the right vagus and coeliac plexus. It accompanies the superior mesenteric artery into the mesentery, dividing into secondary plexuses distributed to parts supplied by the artery: pancreatic, jejunal and ileal, ileocolic, right colic and middle colic. The superior mesenteric ganglion lies superior in the plexus, usually above the superior mesenteric artery's origin. Intestinal sympathetic nerves are motor to the ileocaecal sphincter but inhibitory to the mural musculature; some are vasoconstrictor.

Abdominal Aortic Plexus (Intermesenteric Plexus)

This is formed by branches from the coeliac plexus and ganglia and receives rami from the first and second lumbar splanchnic nerves. It is on the sides and front of the aorta, between the origins of the superior and inferior mesenteric arteries. It consists of four to 12 intermesenteric nerves, connected by oblique branches. It is continuous above with the coeliac plexus and coeliac and aorticorenal ganglia, below with the superior hypogastric plexus. From it parts of testicular, inferior mesenteric, iliac and superior hypogastric plexuses arise; it also supplies the inferior vena cava.

Inferior Mesenteric Plexus

This is chiefly from the aortic plexus but also from the second and lumbar splanchnic nerves. It surrounds the inferior mesenteric artery and is distributed along its branches; thus a left colic plexus supplies the left part of the transverse colon, the descending and the sigmoid colon; a superior rectal plexus supplies the rectum. Near the origin of the inferior mesenteric artery an inferior mesenteric ganglion may occur but more often small ganglia are scattered around the origin of the artery in the proximal part of the plexus. In one study (Southam 1959) an inferior mesenteric ganglion occurred in all of 22 human stillborn infants. The colic sympathetic nerves are inhibitory to mural muscle in the colon and rectum. Branches from parasympathetic pelvic splanchnic nerves ascend occasionally through but usually near the superior hypogastric and inferior mesenteric plexuses to supply the large intestine from the left half of the transverse colon to the rectum (p. 1786 and see below); they are motor to the colic musculature. It is to be emphasized that the parasympathetic supply to the distal colon is largely by these direct branches of the pelvic splanchnic nerves, not via the hypogastric and inferior mesenteric plexuses (Mitchell 1935; Woodburne 1956).

Superior Hypogastric Plexus

The superior hypogastric plexus is anterior to the aortic bifurcation, the left common iliac vein, medial sacral vessels, fifth lumbar vertebral body and sacral promontory and between the common iliac arteries. Often termed the presacral nerve, it is seldom a single nerve and is prelumbar rather than presacral. It lies in extraperitoneal connective tissue; the parietal peritoneum can easily be stripped off its anterior aspect. It varies in breadth and condensation of its constituent nerves and is often a little to one side of the midline (more often to the left); the attachment of the sigmoid mesocolon, containing superior rectal vessels, is to the left of the lower part of the plexus. Scattered neurons occur in it. The plexus is formed by branches from the aortic plexus and third and fourth lumbar splanchnic nerves. It divides into right and left hypogastric 'nerves' which descend to the two inferior hypogastric plexuses. The superior plexus supplies branches to the ureteric, testicular, ovarian and common iliac plexuses. In addition to sympathetic fibres, it may also contain parasympathetic fibres (from pelvic splanchnic nerves) which ascend from the inferior hypogastric plexus; but these fibres usually ascend to the left of the superior hypogastric plexus and across the sigmoid branches of left colic vessels. These parasympathetic fibres are distributed partly along the inferior mesenteric arterial branches and also as independent retroperitoneal nerves, to supply the left part of the transverse colon, left colic flexure, descending and sigmoid colon.

Inferior Hypogastric Plexuses

The superior hypogastric plexus divides caudally into right and left hypogastric 'nerves', each descending in extraperitoneal connective tissue into the pelvis, medial to each internal iliac artery and its branches to become the inferior hypogastric plexus. Each nerve may be single or an elongated plexus of anastomosing filaments. (Hypogastric nerves can scarcely be distinguished from their continuations, the inferior hypogastric plexuses. The latter are joined by pelvic splanchnic nerves, a distinction minimized by the fact that both nerves and plexuses contain sympathetic and parasympathetic fibres. Some authorities prefer to describe a superior hypogastric plexus dividing into

two inferior plexuses.) From each hypogastric nerve branches may pass to the testicular, ovarian and ureteric plexus or to the internal iliac plexuses and to the sigmoid colon; each nerve may be joined initially by the lowest lumbar splanchnic nerve from last lumbar sympathetic ganglion.

Inferior Hypogastric (Pelvic) Plexus

This is in the extraperitoneal connective tissue. In males it is lateral to: the rectum, seminal vesicle, prostate and the posterior part of the urinary bladder. In females each plexus is lateral to: the rectum, uterine cervix, vaginal fornix and the posterior part of the urinary bladder, extending into the broad uterine ligament. Lateral to it are the internal iliac vessels and their branches and tributaries, the levator ani, coccygeus and obturator internus. Posterior are the sacral and coccygeal plexuses and above are the superior vesical and obliterated umbilical arteries. The plexuses contain numerous small ganglia. Each is formed by a hypogastric nerve, conveying most of the sympathetic fibres of the plexus, the remaining few arriving via branches from the ganglia. Parasympathetic fibres are derived from pelvic splanchnic nerves. Preganglionic efferent sympathetic fibres originate in the lower three thoracic and upper two lumbar spinal segments, some relaying in ganglia of the lumbar and sacral parts of the sympathetic trunk, others synapsing in the lower part of the aortic plexus and in the superior and inferior hypogastric plexuses. Preganglionic parasympathetic fibres originate in the second to fourth sacral spinal segments, reach the plexus in the pelvic splanchnic nerves and synapse in it or in walls of viscera supplied by its branches. Numerous branches are distributed to the pelvic and some abdominal viscera, either directly or along their arteries.

Parasympathetic fibres ascend in the hypogastric plexuses or as separate filaments to reach the inferior mesenteric plexus by way of the aortic plexus. By this route the descending and sigmoid parts of the colon receive parasympathetic innervation.

Middle Rectal Plexus

This is formed by fibres from the upper part of the inferior hypogastric plexus to the rectum passing directly or along the middle rectal artery. It connects above with the superior rectal plexus and extends below to the internal anal sphincter. The rectal and anal nerve supply is from:

- the superior rectal plexus
- the middle rectal plexus
- the inferior rectal (haemorrhoidal) nerves, branches of the pudendal nerve.

The parasympathetic preganglionic fibres from the rectal plexuses synapse with postganglionic neurons in the well-developed myenteric plexus, while sympathetic afferents pass through it without interruption. Efferent sympathetic fibres in the rectal plexuses inhibit the expulsive musculature and stimulate the sphincter. Pain impulses traverse the sympathetic and parasympathetic fibres but the parasympathetic afferent and efferent fibres are more active in normal defaecation. Inferior rectal nerves supply motor fibres to the striated external anal sphincter and sensory (somatic) fibres to the lower (ectodermal) part of the anal canal.

Vesical Plexus

Coming from the anterior part of the inferior hypogastric plexus, this comprises many filaments which pass along vesical arteries to the bladder. Branches supply the seminal vesicles and deferent ducts. Many small groups of neurons exist among the nerve fibres in the vesical muscular wall. Sympathetic preganglionic fibres in the plexus are from the lower two thoracic and upper two lumbar spinal segments, synapsing with neurons scattered in the superior and inferior hypogastric plexuses and vesical wall. The parasympathetic preganglionic efferent fibres come from the second to fourth sacral spinal segments and synapse near or in the vesical wall with postganglionic neurons which stimulate its detrusor muscle and inhibit its sphincter. Efferent sympathetic nerves are motor to the sphincter and inhibitor to the detrusor muscle; but some maintain that they are mainly vasomotor and that vesical filling and emptying are controlled by parasympathetic nerves.

Prostatic Plexus

Continued from the lower part of the inferior hypogastric plexus, this is composed of large nerves entering the base and sides of the prostate and contains neurons. It supplies: the prostate, seminal vesicles, prostatic urethra, ejaculatory ducts, corpora cavernosa, corpus spongiosum, membranous and penile urethra and bulbo-urethral glands. The nerves to the corpora cavernosa form two sets, the lesser and greater cavernous nerves, arising from the front of the plexus to join branches from the pudendal nerve and then passing below the pubic arch. The precise localization of the autonomic nerves from the pelvic plexus to the corpora cavernosa has been described by Lepor et al (1985) in the adult male pelvis. Lesser cavernous nerves pierce the fibrous penile sheath proximally to supply

the erectile tissue of the corpus spongiosum and penile urethra. Greater cavernous nerves proceed on the dorsum penis, connect with the dorsal nerve and supply the erectile tissue, some filaments reaching the erectile tissue of the corpus spongiosum. Sympathetic supplies to the male genital organs produce vasoconstriction, the parasympathetic being vasodilator. Seminal vesicles are supplied from the vesical and prostatic plexuses and inferior hypogastric nerves; extensions pass to the ejaculatory and deferent ducts. Contraction of the seminal vesicles and ejaculation are considered to be due to the sympathetic supply, which also inhibits the vesical musculature and stimulates the sphincter during ejaculation, preventing reflux into the bladder. Others have suggested that contraction of the seminal vesicles is under parasympathetic control (Matthews & Raisman 1969).

Uterovaginal Plexus

Uterine nerves arise from the inferior hypogastric plexus, mainly the part in the broad ligament, the uterovaginal plexus, from which branches descend with the vaginal arteries, while others pass directly to the cervix uteri or ascend with or near uterine arteries in the broad ligament. Nerves to the cervix form a plexus in which are small paracervical ganglia, one ganglion sometimes being larger and termed the uterine cervical ganglion. Nerves ascending with the uterine arteries supply the uterine body and tube, connecting with tubal nerves from the inferior hypogastric plexus and with the ovarian plexus. The uterine nerves ramify in the myometrium and endometrium, generally accompanying the vessels. Efferent preganglionic sympathetic fibres are from the last thoracic and first lumbar spinal segments; the sites of their postganglionic neurons are unknown. Preganglionic parasympathetic fibres arise in the second to fourth sacral spinal segments and relay in the paracervical ganglia. Sympathetic activity may produce uterine contraction and vasoconstriction and parasympathetic activity may produce uterine inhibition and vasodilatation, but these activities are complicated by hormonal control of uterine functions.

Vaginal nerves from the lower parts of the inferior hypogastric and uterovaginal plexuses follow the vaginal arteries to supply the vaginal walls, the erectile tissue of the vestibular bulbs and clitoris (cavernous nerves of the clitoris), the urethra and the greater vestibular glands. The nerves contain many parasympathetic fibres which are vasodilator to the erectile tissue.

Lymphoid cells and Thymus

The thymus is one of the two primary lymphoid organs (the other being the bone marrow). It is responsible for the provision of thymus-processed lymphocytes (T lymphocytes) to the whole body. The thymus provides a unique microenvironment in which the T-cell precursors (thymocytes) undergo development, differentiation and clonal expansion; during this process, the exquisite specificity of T-cell responses is acquired, as also is their immune tolerance to the body's own components. These steps involve intimate interactions between thymocytes and other cells (mainly epithelial cells and antigen-presenting cells) and chemical factors of the thymic environment. The organ is also part of the neuroendocrine axis of the body, and it both influences and is influenced by the products of this axis. Its activity, therefore, varies throughout life under the influence of different physiological states, disease conditions and chemical insults such as drugs and pollutants.

Thymic Anatomy

The appearance of the thymus varies considerably with age. It is largest in the early part of life up to the age of about 15, although it persists actively into old age. It is a soft, bilobed organ, its two parts lying close together side by side, joined in the midline by connective tissue which merges with the capsule of each lobe. In children it is more pyramidal in shape and firmer than in later life, when its lymphoid content is reduced. In the fresh state it is deep red due to its rich vascular supply; with age it becomes thinner and greyer before yellowing as adipose tissue infiltrates the organ, a process which is independent of obesity. Its weight also varies with age; at birth it is 10–15 g and rapidly increases to about 20 g, then remains at that level thereafter, although the amount of lymphoid tissue gradually decreases. Each of the two lobes is partially divided by the ingrowth of shallow septa so that superficially it appears lobulated; as fatty atrophy proceeds during ageing this lobulation becomes more distinct. The older thymus can be distinguished from the surrounding mediastinal fat only by the presence of its capsule, although even within greatly atrophied glands there are usually greyer areas around blood vessels, formed by persistent lymphoid tissue.

Position and Relations

The greater part of the thymus lies in the superior and anterior inferior mediastinum, the lower border of the thymus reaching the level of the 4th costal cartilages. Superiorly, extensions into the neck are common, reflecting the (bilateral) embryonic origins of the thymus from the third pharyngeal pouch, it sometimes reaches the inferior poles of the thyroid gland or even higher. Its shape is largely moulded by the adjacent structures. Anterior are the sternum, adjacent parts of the upper four costal cartilages and the sternohyoid and sternothyroid muscles. Posterior are the pericardium and the aortic arch with its branches, the left brachiocephalic vein and the front and sides of the trachea. Ectopic thymic tissue is found in 25% of the population (Goldstein & MacKay 1969); small accessory nodules may occur in the neck representing portions which have become detached during their early descent, or the thymus may be found even more superiorly as thin strands along this path, reaching the thyroid cartilage or above. Connective tissue marking the line of descent during early development may, in some instances, run between the thymus and the parathyroids.

Vessels

Arteries

These are derived mainly from internal thoracic and inferior thyroid artery branches which also supply the surrounding mediastinal connective tissue, although a branch from the superior thyroid artery is also sometimes present. There is no main hilum but arterial branches pass either directly through the capsule or, more often, into the depths of the interlobar septa before entering the thymus at the junction of the cortex and medulla.

Veins

These drain to the left brachiocephalic, internal thoracic and inferior thyroid veins; one or more veins often emerge medially from each lobe of the thymus to form a common trunk opening into the left brachiocephalic vein.

Lymphatics

Afferent lymphatics are absent from the thymus but efferent lymphatics arising from the medulla and corticomedullary junction drain through the extravascular spaces in company with the arteries and veins entering and leaving the thymus. In rodents, large lymphatic vessels draining to perithymic

lymph nodes are often found within the subcapsular cortex but these also receive lymph from other areas of the body; these lymph nodes drain in turn to neighbouring regional nodes (Goldstein & MacKay 1969). Whether there is a similar perithymic lymphatic drainage in humans remains unknown.

Innervation

Thymic innervation is derived from the sympathetic chain via the cervicothoracic (stellate) ganglion (or from the ansa subclavia) and the vagus. Branches from the **phrenic** nerve and descendens cervicalis are distributed mainly to the capsule of the thymus. During development (Hammar 1935), vagal innervation of the thymus commences in the neck before its descent into the thorax. The two lobes are innervated separately through their dorsal, lateral and medial aspects and rich neural plexuses are formed in the medulla. After its descent, the thymus receives the sympathetic nerves along vascular routes, their terminals branching radially and forming with the vagal fibres a plexus at the corticomedullary junction. Innervation is complete by the onset of thymic function. While many of the autonomic nerves are doubtless vasomotor, many terminal branches also (at least in rodents) leave their perivascular pathways and pass among the cells of the thymus, particularly the medulla, suggesting that they may have other roles. The medulla also contains a variety of non-lymphoid cells, including cells positive for vasoactive intestinal polypeptide (VIP), acetylcholinesterase (AChE) large, non-myoid cells and cells containing oxytocin, vasopressin and neurophysin, with possible neural crest origin. Clearly, the roles of the nervous system and other neuroendocrine elements in the overall biology of the thymus are far from being understood and suggest many intriguing possibilities.

Thoracic cavity and the heart

The volume enclosed within the thoracic cavity does not correspond with that enclosed by the osseous thorax because the lower part of the space surrounded by the bony elements is encroached upon by the diaphragm and the mobile and distensible organs within the upper abdomen. The capacity of the thoracic cavity also varies with posture and respiration, both affecting the position and relations of the thoracic organs. Its arbitrary upper limit is usually taken as the oblique plane of its inlet at the first rib, but the pulmonary apices and pleural cavities extend above this level into the neck, reaching the level of the neck of the rib.

Upper Opening (Inlet) of Thorax

The boundaries are formed by the skeleton described on page 545. The structures passing through the opening can be divided into two groups:

- those in or near the medial plane
- those on each side closely related to the cervical parts of the lungs.

Near the midline: behind the manubrium of the sternum, the lowest parts of the sternohyoid muscles enter the thorax, and behind them are the sternothyroid muscles along with vestiges of the thymus gland and the inferior thyroid veins passing down to empty into the brachiocephalic veins. In children, particularly, the left brachiocephalic vein itself may be in the thoracic inlet. Posteriorly, the trachea and the oesophagus, with the left recurrent laryngeal nerves, pass through the median part of the opening. The thoracic duct also passes through the opening behind the left margin of the oesophagus. Anterior to the vertebral column are the prevertebral longus colli muscles and the anterior longitudinal ligament. On each side: the upper part of the pleura and the pulmonary apex occupy the inlet. Between the pleura and neck of the first rib, mediolaterally, are found the sympathetic trunk, the superior intercostal artery and the ventral branch of the first thoracic nerve as it passes superolaterally to join the brachial plexus. Anteriorly, the internal thoracic artery enters the thorax between the pleura and the first costal cartilage while, medial to the artery, its vein leaves the thorax.

On the right : the brachiocephalic artery leaves the thorax between the trachea and pleura. The vagus nerve, having passed between subclavian artery and vein, is between the pleura and the brachiocephalic artery at the inlet. The right brachiocephalic vein enters the thorax anterolateral to its artery. The right **phrenic** nerve crosses the internal thoracic artery and is lateral to the brachiocephalic vein behind the first costal cartilage.

On the left : the left common carotid and subclavian arteries leave the thorax between the pleura and trachea, the left vagus nerve descending lateral to the interval between them. Anterolateral to this is found the left brachiocephalic vein. The left **phrenic** nerve passing inferomedially crosses anterior to the internal thoracic artery at a higher level than the right. At the inlet, the left **phrenic** nerve is found between the left brachiocephalic vein anterolaterally and the subclavian and common carotid arteries posteromedially.

Lower Opening (Outlet) of Thorax

This extensive opening is wider transversely and slopes obliquely down and backwards, so that the vertical extent of the cavity is much longer posteriorly than it is anteriorly. The diaphragm (p. 815) closes the opening and forms a convex floor for the cavity. It is flatter centrally than at its peripheral attachments. It is higher on the right and, in cadavers, this side of the floor reaches the level of the upper border of the fifth costal cartilage. On the left, the diaphragm reaches only to the level of the sixth cartilage. From the summit of each side, the diaphragm slopes abruptly down to its sternal, costal and vertebral attachments. The muscle is short anteriorly, progressively longer laterally, and it is longest and with a much more marked slope posteriorly, where the space between the diaphragm and the posterior thoracic wall narrows rapidly as it extends inferiorly.

Divisions of Thoracic Cavity

The thoracic cavity is divided by the mediastinum, itself formed by the mass of structures between the lungs which extend from the sternum to the vertebral column and from the thoracic inlet to the diaphragm. The heart is in the mediastinum, enclosed by the pericardium. The lungs occupy the right and left regions of the thorax, each covered by a serosal membrane, the pleura, which also lines the corresponding half of the thorax and the lateral aspect of the mediastinum.

For description, the mediastinum is arbitrarily divided into superior and inferior parts. The superior part extends from the thoracic inlet to an oblique (transverse thoracic) plane passing through the lower edge of the manubrium of the sternum and lower border of the fourth thoracic vertebra. The inferior part, below this plane, is subdivided into an anterior part in front of the pericardium, a posterior

component behind this and the diaphragm, and a middle component, containing the pericardium and the heart together with the large vessels entering or leaving it. Detailed accounts of the mediastinal contents are included with descriptions of the respiratory organs; the heart; and the oesophagus.

Pericardium

The pericardium contains the heart and the juxtacardiac parts of its great vessels. It consists of two components, the fibrous and the serosal pericardium. The fibrous pericardium is a sac made of tough connective tissue, fully surrounding the heart without being attached to it. This fibrous sac develops by a sequential process of cavitation of the embryonic body wall by expansion of the secondary pleural cavity; thus its lateral walls are clothed externally by parietal mediastinal pleura. The serosal pericardium consists of two sacs of serosal membrane, one inside the other, the inner (visceral) one adhering to the heart and forming its outer covering known as the epicardium, while the outer (parietal) one lines the internal surface of the fibrous pericardium. The two serosal surfaces are apposed and separated by a film of fluid, thus allowing movement of the inner membrane and the heart adhering to it, except at the arterial and venous areas of the pericardium where the two serosal membranes merge. The latter constitute two parietovisceral lines of serosal reflexion (see below). The separation of the two membranes of the serosal pericardium creates a narrow space, the pericardial cavity, which provides a complete cleavage between the heart and its surroundings thus allowing it some freedom to move and change shape.

Fibrous Pericardium

The fibrous pericardium is roughly conical and clothes the heart. Superiorly, it is continuous exteriorly with the adventitia of the great vessels, while inferiorly it is attached to the central tendon of the diaphragm and a small muscular area of its left half. Above, the fibrous pericardium not only blends externally with the great vessels, but is continuous with the pretracheal fascia. Anteriorly it is also attached to the posterior surface of the sternum by superior and inferior sternopericardial ligaments, although the extent of these 'ligaments' is extremely variable, the superior one often being undetectable. By these connections, the pericardium is securely anchored and maintains the general thoracic position of the heart, serving as the 'cardiac seat belt'.

Anteriorly, the fibrous pericardium is separated from the thoracic wall by the lungs and the pleural coverings. However, in a small area behind the lower left half of the body of the sternum and the sternal ends of left fourth and fifth costal cartilages, the pericardium is in direct contact with the thoracic wall. Until it regresses, the lower end of the thymus is also anterior to the upper pericardium. Posteriorly are the principal bronchi, the oesophagus, the oesophageal plexus, the descending thoracic aorta, and the posterior parts of the mediastinal surface of both lungs. Laterally are the pleural coverings of the mediastinal surface of the lungs. The **phrenic** nerve, with its accompanying vessels, descends between the fibrous pericardium and mediastinal pleura on each side. Inferiorly, the pericardium is separated by the diaphragm from the liver and fundus of the stomach.

Vessels receiving extensions of the fibrous pericardium are the aorta, the superior vena cava, the right and left pulmonary arteries and the four pulmonary veins. The inferior vena cava, traversing the central tendon, has no such covering.

Serosal Pericardium

The serosal pericardium is a closed sac within the fibrous pericardium, having a visceral and a parietal layer. The visceral layer, or epicardium, covers the heart and great vessels and is reflected into the parietal layer, which lines the internal surface of the fibrous pericardium. The reflexions of the serosal layer are arranged as two complex 'tubes', the aorta and pulmonary trunk being enclosed in one and the superior and inferior venae cavae and the four pulmonary veins in the other. The tube surrounding the veins has the shape of an inverted J and the cul-de-sac within its curve is behind the left atrium and is termed the oblique sinus. A passage between the two pericardial 'tubes' is the transverse sinus. This has the aorta and pulmonary trunk in front and the atria and great veins behind. The arrangement of the oblique and transverse sinuses, along with that of the main 'principal' cavity, is further affected by the development of complex three-dimensional pericardial recesses between adjacent structures. (For details, illustrations and bibliography see Vesely & Cahill 1986.) These recesses can be grouped according to the siting of their orifices or 'mouths'. From the principal pericardial cavity, the postcaval recess projects towards the left behind the atrial termination of the superior vena cava. It is limited above by the right pulmonary artery and below by the upper right pulmonary vein. Its mouth opens superolaterally to the right. The right and left pulmonary venous recesses each project medially and upwards on the back of the left atrium between the superior and inferior pulmonary veins on each side, indenting the side walls of the oblique sinus. The superior aortic recess extends from the transverse sinus. From its mouth, located inferiorly, it ascends posterior to, then right of, the ascending aorta to end at the level of the sternal angle. The inferior aortic recess, also extending from the transverse

sinus, is a diverticulum descending from a superiorly located mouth to run between the lower ascending part of the aorta and the right atrium. The left pulmonary recess, mouth under the fold of the left vena cava, passes to the left between the inferior aspect of the left pulmonary artery and upper border of the superior left pulmonary vein. The right pulmonary recess lies between the lower surface of the proximal part of the right pulmonary artery and upper border of the left atrium.

A triangular fold of serosal pericardium is reflected from the left pulmonary artery to the subjacent upper left pulmonary vein as the fold of the left superior vena cava. It contains a fibrous ligament, a remnant of the obliterated left common cardinal vein. This descends anterior to the left pulmonary hilum from the upper part of the left superior intercostal vein to the back of the left atrium, where it is continuous with the oblique vein of the left atrium. The left common cardinal vein may persist as a left superior vena cava which then replaces the oblique vein of the left atrium and empties into the coronary sinus. When both common cardinal veins persist as right and left superior venae cavae, the transverse anastomosis between them, normally forming the left brachiocephalic vein, may be small or absent. When there is a left superior vena cava, it is joined by the left superior intercostal vein.

Vessels and Nerves

The arteries of the pericardium are derived from the internal thoracic and musculophrenic arteries and the descending thoracic aorta. The veins are tributaries of the azygos system. The nerve supply is from the vagus together with phrenic nerves and the sympathetic trunks.

Structure

The fibrous pericardium is compact collagenous fibrous tissue. The serosal pericardium is a single layer of flat cells on a thin subserosal layer of connective tissue which blends with the fibrous pericardium in the parietal membrane and with the interstitial myocardial tissue in the visceral membrane. On the cardiac side, the subserosal layer contains fat, this being greatest along the ventricular side of the atrioventricular groove, the inferior cardiac border and the interventricular grooves. The main coronary vessels and their larger branches are embedded in this fat, its amount being related to the general extent of body fat and gradually increasing with age.

Pericardial Puncture

Pericardial puncture can be performed either in the fifth or sixth left intercostal space near the sternum to avoid the internal thoracic artery, or at the left costoxiphoid angle, passing up and backwards into the pericardial sac. The serosal pericardium extends on the pulmonary trunk, anterior to the transverse sinus, as far as the arterial ligament.

Heart

Inferior, Diaphragmatic Surface of the Heart

Largely horizontal, it slopes down and forwards a little towards the apex. It is formed by the ventricles (chiefly the left) and rests mainly upon the central tendon but also, apically, on a small area of the left muscular part of the diaphragm. It is separated from the anatomic base by the atrioventricular groove and is traversed obliquely by the posterior interventricular groove.

Left Surface of the Heart

Facing up, back and to the left, this consists almost entirely of the obtuse margin of the left ventricle, but has a small part of the left atrium and its auricle contributing superiorly. Convex and widest above, and crossed here by the atrioventricular groove, it narrows to the cardiac apex. It is separated by the pericardium from the left phrenic nerve and its accompanying vessels, and by the left pleura from the deep concavity of the left lung.

Right Surface of the Heart

A rounded surface is formed by the right atrial wall and is separated from the mediastinal aspect of the right lung by the pericardium and the pleural coverings. Its convexity merges below into the short intrathoracic part of the inferior vena cava and above into the superior vena cava. The terminal groove (sulcus terminalis) is a prominent landmark between the true atrial and the venous components of the right atrium, curving approximately along the junction of the sternocostal and right surfaces (10.29).

Upper Border of the Heart

This is atrial (mainly the left atrium). Anterior to it are the ascending aorta and the pulmonary trunk. At its extremity the superior vena cava enters the right atrium.

Right Border of the Heart

Corresponding to the right atrium, its profile is slightly convex to the right and it approaches the vertical.

Inferior Border of the Heart

Also known as the acute margin of the heart, it is sharp, thin and nearly horizontal. It extends from the lower limit of the right border to the apex and it is formed mainly by the right ventricle, with a small contribution from the left ventricle near the apex.

Left Border of the Heart

Also known as the obtuse margin, it separates the sternocostal and left surfaces. It is round and mainly formed by the left ventricle but, to a slight extent superiorly, is formed by the auricle of the left atrium. It descends obliquely, convex to the left, from the auricle to the cardiac apex.

Cardiac Chambers and Internal Features

The right and left chambers of the heart will be described in sequence in terms of their general form, their walls and their internal features. The two sides have much in common, such as the structure of valvar leaflets, tendinous cords, and papillary muscles of atrioventricular (inlet) valves, and the architecture of the cusps of the pulmonary and aortic (outlet) valves. Repetition, as far as possible, will be kept to a minimum.

Right Atrium

General and External Features

The interatrial septum (or atrial septum) is oblique, so the right atrium is anterior as well as to the right of the left atrium, also extending inferior to it. Its walls form the right upper sternocostal surface, the convex right (pulmonary surface) and a little of the right side of the anatomic base. The superior vena cava opens into its dome and the inferior vena cava into its lower posterior part. An extensive muscular pouch, the auricle or appendage, projects anteriorly to overlap the right side of the ascending aorta. The auricle is a broad, triangular structure and has a wide junction with the true atrial component of the atrium. The junction between the venous part (sinus venarum) and the atrium proper is marked externally by a shallow groove, the sulcus terminalis, extending between the right sides of the openings of the two venae cavae. The sulcus terminalis corresponds, internally, to the terminal crest (crista terminalis) which is the site of origin of the extensive pectinate muscles arising serially at right angles from the crest. Posteriorly, the vertical interatrial groove descends to the crux. Anteriorly, the right atrium is related to the anterior part of the mediastinal surface of the right lung, separated from it by pleura and pericardium. Laterally, the atrium is also related to the mediastinal surface of the right lung, but anterior to its hilum and separated from it by the pleura, right **phrenic** nerve and pericardiaco**phrenic** vessels and pericardium. Posteriorly and to the left, the atrial septum and the surrounding infolded atrial walls separate the right from the left atrium (the mural infolding being indicated by the extensive interatrial groove). Posteriorly and to the right are the right pulmonary veins. Medially are the ascending aorta and, to a lesser extent, the root of the pulmonary trunk and its bifurcation.

Arch of the Aorta

Arch of the Aorta

The aortic arch continues the ascending aorta. Its origin, slightly to the right, is level with the upper border of the second right sternocostal joint. The arch first ascends diagonally back and to the left over the anterior surface of the trachea, then back across its left side and finally descends left of the fourth thoracic vertebral body, continuing as the descending thoracic aorta. Its end is level with the sternal end of the second, left costal cartilage. Thus, the aortic arch lies wholly in the superior mediastinum. It curves around the peduncle of the left lung, and extends upwards to the mid-level of the manubrium of the sternum. Its diameter at the origin is the same as in the ascending aorta, about 28 mm, but it is reduced to 20 mm at the end, after the issue of its large collateral branches. At the border with the thoracic aorta, a small stricture (aortic isthmus), followed by a dilatation, can be recognized. In fetal life the isthmus lies between the origin of the left subclavian artery and the opening of the ductus arteriosus.

Relations

Anteriorly and to the left is the left mediastinal pleura, deep to which it is crossed by four nerves: the left **phrenic**, left lower cervical vagal cardiac branch, left superior cervical sympathetic cardiac branch and left vagus, in anteroposterior order. As the left vagus crosses the arch its recurrent laryngeal branch hooks below the vessel left and behind (developmentally caudal to) the ligamentum arteriosum and then ascends on the arch's right. The left superior intercostal vein ascends obliquely forwards on the arch, superficial to the left vagus, deep to the left **phrenic** nerve. The left lung and pleura separate all these from the thoracic wall. Posterior to the right are the trachea and deep cardiac plexus, the left recurrent laryngeal nerve, oesophagus, thoracic duct and vertebral column. Above, the brachiocephalic, left common carotid and left subclavian arteries arise from its convexity, crossed anteriorly near their origins by the left brachiocephalic vein. Below are the pulmonary bifurcation, left principal bronchus, ligamentum arteriosum, superficial cardiac plexus and left recurrent laryngeal nerve. (Best viewed from the left, the concavity of the aortic arch is the upper curved limit through which structures gain access or exit through the hilum of the left lung.)

The fetal aortic lumen narrows between the origin of the left subclavian artery and the attachment of the ductus arteriosus, as the aortic isthmus; beyond the ductus arteriosus the vessel presents a fusiform aortic spindle, the junction of the two parts being marked inferiorly by an indentation; these features persist variably in adults.

Common Carotid Arteries

The right and left carotid arteries differ in length and origin. The right carotid, exclusively cervical, originates from the brachiocephalic trunk behind the right sternoclavicular joint. The left carotid originates directly from the aortic arch immediately posterolateral to the brachiocephalic trunk and therefore has both thoracic and cervical parts.

Thoracic Part of the Left Common Carotid Artery

This part ascends until level with the left sternoclavicular joint, where it enters the neck. It is 20–25 mm long and it lies at first in front of the trachea, then it inclines to the left.

Relations

Anterior are the sternohyoid and sternothyroid, the anterior parts of the left pleura and lung, the left brachiocephalic vein and the thymic remnants, separating it from the manubrium; posterior are the trachea, left subclavian artery, left border of the oesophagus, left recurrent laryngeal nerve and thoracic duct. To the right are (below) the brachiocephalic trunk and (above) the trachea, inferior thyroid veins and thymic remains; to the left are the left vagus and **phrenic** nerves, left pleura and lung.

Subclavian Artery

The right subclavian arises from the brachiocephalic trunk, the left from the aortic arch. For description, each is divided into a first part, from its origin to the medial border of the scalenus anterior, a second part behind this muscle and a third part from the muscle's lateral margin to the first rib's outer border, where the artery becomes axillary. Each subclavian artery arches over the cervical pleura and pulmonary apex. Their first parts differ, the second and third parts are almost identical.

First Part of Right Subclavian Artery

The right subclavian, branching from the brachiocephalic trunk behind the upper border of the right sternoclavicular joint, passes superolaterally to the medial margin of the scalenus anterior. It ascends about 2 cm above the clavicle but this varies.

Relations

The artery is deep to the skin, superficial fascia, platysma, anterior supraclavicular nerves, deep fascia, clavicular attachment of the sternocleidomastoid, sternohyoid and sternothyroid. It is at first behind the right common carotid's origin; more laterally it is crossed by the vagus nerve, the cardiac branches of the vagus and the sympathetic chain and by internal jugular and vertebral veins; the subclavian sympathetic loop encircles it. The anterior jugular vein diverges laterally in front of it, separated by the sternohyoid and sternothyroid. Below and behind the artery are the pleura and pulmonary apex but separated by the suprapleural membrane (p. 1663), the ansa subclavia, an accessory vertebral vein and the right recurrent laryngeal nerve (curving round inferoposterior to the vessel).

First Part of Left Subclavian Artery

This springs from the aortic arch, behind the left common carotid, level with the disc between the third and fourth thoracic vertebrae; it ascends into the neck, then arches laterally to the medial border of the scalenus anterior.

Relations

In the thorax it is related, anteriorly to the left common carotid artery and left brachiocephalic vein, separated by the left vagus, cardiac and **phrenic** nerves. Superficial to these the anterior pulmonary margin, pleura, sternothyroid and sternohyoid are between the vessel and the upper left area of the manubrium sterni. Posterior are the left side of the oesophagus, the thoracic duct and longus colli; it is in contact posterolaterally with the left lung and pleura. Medial are the trachea, the left recurrent laryngeal nerve, oesophagus and thoracic duct. Laterally the artery grooves the mediastinal surface of the left lung and pleura which also encroach on its anterior and posterior aspects.

In the neck, near the medial border of the scalenus anterior, the artery is crossed anteriorly by the left **phrenic** nerve and the termination of the thoracic duct. Otherwise anterior relations are as previously described for the first part of the right subclavian artery. Posteriorly and inferiorly, the relations of both vessels are identical but the left recurrent laryngeal nerve, medial to the left subclavian artery in the thorax, is not directly related to its cervical part.

Second Part of Subclavian Artery

This is behind the scalenus anterior; it is short and the highest part of the vessel.

Relations

Anterior are the skin, superficial fascia, platysma, deep cervical fascia, sternocleidomastoid and scalenus anterior; the right **phrenic** nerve is often described as separated from the second part by the scalenus anterior, but crossing the first part on the left; Qvist (1977) stated that both nerves are anterior to the muscle. Postero-inferior are the supracleural membrane, pleura and lung and the lower trunk of the brachial plexus; superior are the upper and middle trunks of the plexus; the subclavian vein is antero-inferior, separated by the scalenus anterior.

Third Part of Subclavian Artery

This descends laterally from the lateral margin of the scalenus anterior to the outer border of the first rib, where it becomes axillary; it is the most superficial part of the artery and lies partly in the supraclavicular triangle, where its pulsations may be felt and it may be compressed.

Relations

Anterior are the skin, superficial fascia, platysma, supraclavicular nerves and deep cervical fascia. The external jugular vein crosses its medial end and here receives the suprascapular, transverse cervical and anterior jugular veins, together often forming a venous plexus. The nerve to the subclavius descends between the veins and the artery; the latter is terminally behind the clavicle and subclavius, where it is crossed by the suprascapular vessels. The subclavian vein is antero-inferior and the lower trunk of the brachial plexus is postero-inferior, between the artery and the scalenus medius (and on the first rib). Superolateral are the upper and middle trunks of the brachial plexus (palpable here) and the inferior belly of the omohyoid. Inferior is the first rib.

Cervical veins

Internal Jugular Vein

This large vein collects blood from the skull, brain, superficial parts of face and much of the neck. It begins at the cranial base in the posterior compartment of the jugular foramen, continuous with the sigmoid sinus. At its origin is its superior bulb, which is below the posterior part of the tympanic floor. The vein descends in the carotid sheath, uniting with the subclavian, posterior to the sternal end of the clavicle, to form the brachiocephalic vein. It is also dilated near its end as its inferior bulb, above which it contains a pair of valves. Posterior to the vein, from above, are: the rectus capitis lateralis, transverse process of atlas, levator scapulae, scalenus medius and cervical plexus, scalenus anterior, **phrenic** nerve, thyrocervical trunk, vertebral vein and first part of subclavian artery; on the left it also crosses anterior to the thoracic duct. Medial to the vein are the internal and common carotid arteries and the vagus nerve between vein and arteries but posterior to them. Superficially the vein is overlapped above, then covered below by sternocleidomastoid and crossed by the posterior belly of the digastric and the superior belly of omohyoid. Superior to the digastric, the parotid gland and styloid process are superficial, the accessory nerve, posterior auricular and occipital arteries crossing the vein. Between the digastric and the omohyoid, the sternocleidomastoid arteries and inferior root of the

ansa cervicalis cross it, but the nerve often passes between the vein and the common carotid. Below the omohyoid, it is covered by the infrahyoid muscles and the sternocleidomastoid and it is crossed by the anterior jugular vein. Deep cervical lymph nodes lie along the vein, mainly on its superficial aspect. At the root of the neck the right internal jugular is separated from the common carotid, but the left usually overlaps its artery. At the base of the skull the internal carotid artery is anterior, separated from the vein by the ninth to twelfth cranial nerves.

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Veins of the Thorax

Brachiocephalic Veins

The brachiocephalic (innominate) veins, two large vessels at the junction of the neck and thorax, are the united trunks of the internal jugular and subclavian veins. Both are devoid of valves.

Right Brachiocephalic Vein

About 2.5 cm long, it begins posterior to the sternal end of the right clavicle, and descends almost vertically to join the left brachiocephalic forming the superior vena cava posterior to the lower border of the first right costal cartilage, near the right sternal border. It is anterolateral to the brachiocephalic artery and right vagus nerve. The right pleura, **phrenic** nerve and internal thoracic artery are posterior to it above, becoming lateral below. Its tributaries are the right vertebral, internal thoracic, inferior thyroid and sometimes the first right posterior intercostal veins.

Left Brachiocephalic Vein

Some 6 cm long, it begins posterior to the sternal end of the left clavicle, anterior to the cervical pleura. It descends obliquely to the right, posterior to the upper half of the manubrium sterni, to the sternal end of the first right costal cartilage, uniting here with the right brachiocephalic to form the superior vena cava. It is separated from the left sternoclavicular joint and manubrium by the sternohyoid and sternothyroid, the thymus or its remains and areolar tissue; terminally it is overlapped by the right pleura. It crosses anterior to the left internal thoracic, subclavian and common arteries, left **phrenic** and vagus nerves, trachea and brachiocephalic artery. The aortic arch is inferior to it. The vein's tributaries are the left vertebral, internal thoracic, inferior thyroid, superior intercostal, sometimes the first left posterior intercostal, thymic and pericardial veins.

Surface Anatomy

The brachiocephalic veins can be projected as broad bands 1.5 cm wide from the sternal ends of the clavicles to the parasternal lower border of the first right costal cartilage.

Variations

The brachiocephalic veins may enter the right atrium separately, the right vein descending like a normal superior vena cava; a left superior vena cava may have a slender connection with the right and

then cross the left side of the aortic arch to pass anterior to the left pulmonary hilum before turning to enter the right atrium. It replaces the oblique atrial vein and coronary sinus and receives all the latter's tributaries. This abnormality, due to persistence of an early fetal condition, is normal in birds and some mammals. The left brachiocephalic vein sometimes projects above the manubrium (more frequently in childhood), crossing the suprasternal fossa in front of the trachea.

Internal Thoracic (Mammary) Veins

The internal thoracic veins are venae comitantes to the inferior half of the internal thoracic artery; they have several valves. Near the third costal cartilages the veins unite to ascend medial to the artery, ending in their brachiocephalic vein. Tributaries correspond to branches of the artery, and include a pericardiophrenic vein.

Inferior Thyroid Veins

The inferior thyroid veins arise in a glandular venous plexus, which also connects with the middle and superior thyroid veins. These veins form a pretracheal plexus from which the left inferior vein descends to join the left brachiocephalic, the right descending obliquely across the brachiocephalic artery to the right brachiocephalic vein, at its junction with the superior vena cava; the inferior thyroid veins often open in common into the vena cava or left brachiocephalic vein. They drain the oesophageal, tracheal and inferior laryngeal veins and have valves at their terminations.

Left Superior Intercostal Vein

The left superior intercostal vein drains the second and third (sometimes fourth) left posterior intercostal veins, ascending obliquely forwards across the left aspect of the aortic arch, lateral to the left vagus, medial to the left phrenic nerve, to open into the left brachiocephalic vein. It usually receives the left bronchial veins, sometimes the left pericardiophrenic; it connects inferiorly with the accessory hemiazygos vein.

Superior Vena Cava

The superior vena cava is about 7 cm in length, formed by the junction of the brachiocephalic veins, and has no valves. It returns to the heart blood from the superior half of the body. It begins behind the lower border of the first right costal cartilage near the sternum, descends vertically behind the first and second intercostal spaces, ending in the upper right atrium behind the third right costal cartilage; its inferior half is within the fibrous pericardium, which it pierces level with the second costal cartilage. Covered anterolaterally by serous pericardium from which projects a retrocaval recess, it is slightly convex to the right.

Relations

Anterior are the anterior margins of the right lung and pleura, the pericardium intervening below; these separate the vein from the internal thoracic artery and first and second intercostal spaces, and second and third costal cartilages; posteromedial are the trachea and right vagus nerves and posterolateral the right lung and pleura; posterior is the right pulmonary hilum. Right lateral are the right phrenic nerve and pleura, left lateral the brachiocephalic artery and ascending aorta, the latter overlapping it.

Surface Anatomy

The superior vena cava, 2 cm wide, is partly behind but projects well beyond the right sternal margin, from the lower border of the first to the lower border of the third right costal cartilage. Its lateral border is visible in anteroposterior radiographs.

Tributaries

These are: the azygos vein and small veins from the pericardium and other mediastinal structures.

Azygos Vein

An origin from the posterior aspect of the inferior vena cava, at or below the level of the renal veins, is to be expected from its development but it is not constant (Gladstone 1929). Such a lumbar azygos vein frequently occurs, ascending anterior to the upper lumbar vertebrae. The vein may pass behind the right crus of the diaphragm or pierce it. It may traverse the aortic opening on the right of the cisterna chyli. Anterior to the twelfth thoracic vertebral body it is joined by a large vessel formed by the right ascending lumbar and right subcostal veins, which passes forward and right of the twelfth thoracic vertebra behind the right crus. This common trunk may, in the absence of a lumbar azygos, form the azygos itself. Whatever its origin, the azygos vein ascends in the posterior mediastinum to

the fourth thoracic vertebra, arching forward above the right pulmonary hilum to end in the superior vena cava, before the latter pierces the pericardium. It is anterior to the lower eight thoracic vertebral bodies (see below), anterior longitudinal ligament and right posterior intercostal arteries. Right lateral are the right greater splanchnic nerve, lung and pleura; left lateral in most of its course are the thoracic duct and aorta and, where it arches forward, the oesophagus, trachea and right vagus. In the lower thorax it is covered anteriorly by a recess of the right pleural sac and oesophagus, emerging from behind the latter to ascend behind the right hilum. Because of the closeness of the azygos vein to the right posterolateral aspect of the descending thoracic aorta, aortic pulsations may assist venous return in azygos and hemiazygos veins.

Tributaries

The azygos vein drains: the right posterior intercostal veins except the first, the veins from the second to fourth intercostal spaces usually via a right superior intercostal vein, the hemiazygos and accessory hemiazygos veins, oesophageal, mediastinal and pericardial veins and, near its end, right bronchial veins. When it begins as a lumbar azygos, the common trunk formed by the right ascending lumbar and subcostal veins is its largest tributary. Imperfect valves occur in the azygos vein, some tributaries having complete valves.

Hemiazygos Vein

It starts on the left like the azygos; ascending anterior to the vertebral column to the eighth thoracic level, it crosses the column posterior to the aorta, oesophagus and thoracic duct to end in the azygos vein. Its tributaries are the lower three posterior intercostal veins, a common trunk formed by the left ascending lumbar and subcostal veins and oesophageal and mediastinal rami. Its lower end often connects with the left renal vein.

Accessory Hemiazygos Vein

It descends to the left of the vertebral column, receiving veins from the fourth (or fifth) to eighth intercostal spaces and sometimes the left bronchial veins. It crosses the seventh thoracic vertebra to join the azygos vein. It sometimes joins the hemiazygos, their common trunk opening into the azygos vein.

Variations of the Azygos Veins

They vary much in their mode of origin, course, tributaries, anastomoses and termination. For a survey consult Grzybiak et al (1975), who consider the accessory hemiazygos most variable, draining into the left brachiocephalic, azygos or hemiazygos. The arrangement shown in 10.172 represents a common pattern. In about 1 or 2% of subjects according to Anson (1963) there are left and right independent azygos veins (the early embryonic form) and occasionally a single azygos without hemiazygos tributaries, in a midline position. In more than 95% a main 'right-sided' azygos and at least some representative of hemiazygos veins exist. The latter vary, one or the other being absent or poorly developed. Retro-aortic transvertebral connections from hemiazygos and accessory hemiazygos veins to the azygos are also extremely variable; there may be from one to five, or more; when either hemiazygos is absent, intercostal veins involved cross vertebral bodies to end in the azygos. These transvertebral routes are often very short, since the azygos vein is more commonly anterior to the vertebral column (Anson 1963) and often passes left of the midline in part of its course.

Inferior vena cava

Inferior Vena Cava

The inferior vena cava conveys blood to the right atrium from all structures below the diaphragm. It is formed by the junction of the common iliac veins anterior to the fifth lumbar vertebral body, a little to its right. It ascends anterior to the vertebral column, to the right of the aorta. Reaching the liver, it is contained in a deep groove on its posterior surface or sometimes in a tunnel completed by a band of liver tissue. It perforates the tendinous part of the diaphragm between its median and right 'leaves' and inclines slightly anteromedially. Passing through the fibrous pericardium and through a posterior inflexion of the serous pericardium it opens into the inferoposterior part of the right atrium. Anterior and left of its atrial orifice is a semilunar valve of the inferior vena cava, relatively less prominent in adults, but large and overtly functional in the fetus. The vessel is otherwise devoid of valves.

Relations of the Abdominal Part

Anteriorly the inferior vena cava is overlapped at its commencement by the right common iliac artery and covered, below the horizontal part of the duodenum, by the posterior parietal peritoneum. It is crossed obliquely by the root of the mesentery and its contained vessels and nerves and by the right testicular or ovarian artery. It ascends behind the head of the pancreas and then the superior part of the duodenum, separated from it by the common bile duct and portal vein. Above the duodenum it is again covered by peritoneum of the posterior wall of the epiploic foramen, separating it from the right free border of the lesser omentum and its contents. Above this the liver is anterior.

Posterior are the lower three lumbar vertebral bodies, their intervening 'discs' and the anterior longitudinal ligament, the right psoas major, right sympathetic trunk, and third and fourth right lumbar arteries; superior to these are the right crus (partially separated by the medial part of the right suprarenal gland and the right coeliac ganglion) and the right renal, suprarenal and inferior **phrenic** arteries.

Right lateral are the right ureter, the descending part of the duodenum, the medial border of the right kidney and right lobe of the liver. Left lateral are the aorta and above this the right crus and caudate lobe.

Relations of the Thoracic Part

This part of the inferior vena cava is very short, partly inside and partly outside the pericardial sac. The extrapericardial part is separated from the right pleura and lung by the right **phrenic** nerve. The intrapericardial part is covered, except posteriorly, by inflected serous pericardium.

Surface Anatomy

The vein begins in, or just below, the transtuberular plane, its centre 2.5 cm right of the midline; about 2.5 cm wide, it ends behind the sternal end of the sixth right costal cartilage. A band from its lower end to a part of the inguinal ligament centred at a point 1 cm medial to the midinguinal point indicates the common and external iliac veins on each side.

Variations

Numerous anomalies occur and are attributable to arrests or errors in its complex formation. It is sometimes replaced, below the level of the renal veins, by two more or less symmetrical vessels, often associated with the failure of interconnection between the common iliac veins, and due to persistence on the left of a longitudinal channel (usually supra- or subcardinal) which normally disappears in early fetal life. In complete visceral transposition, the inferior vena cava is left of the aorta.

Clinical Anatomy

Thrombosis of the inferior vena cava leads to oedema of the legs and back, without ascites. Collateral venous circulation is soon established by enlargement of either the superficial or deep veins, or both; the epigastric, circumflex iliac, lateral thoracic, thoraco-epigastric, internal thoracic, posterior intercostal, external pudendal and lumbovertebral anastomotic veins connect it with the superior vena cava; deep connections are made through the azygos, hemiazygos and lumbar veins. Vertebral venous plexuses may also provide effective collateral circulation between the venae cavae (Batson 1957).

Tributaries

These are the common iliac, lumbar, right testicular or ovarian, renal, right suprarenal, inferior **phrenic** and hepatic veins.

Lymphatic system

In adults the thoracic duct including the confluence of lymph trunks (or the cisterna chyli in the small proportion in whom the latter is saccular) is 38–45 cm in length, extending from the second lumbar vertebra to the base of the neck. Starting from the superior pole of the confluence near the lower border of the twelfth thoracic vertebra, it traverses the diaphragm's aortic aperture, then ascends the posterior mediastinum, right of the midline, between the descending thoracic aorta (on its left) and the azygos vein (on its right). Posterior to it is the vertebral column (vertebral bodies, symphyses, anterior longitudinal ligament), the right aortic intercostal arteries and terminal segments of the hemiazygos and accessory hemiazygos veins. Anterior to it are the diaphragm and oesophagus; a recess of the right pleural cavity may separate the duct and oesophagus. Reaching the level of the fifth thoracic vertebral body it gradually inclines to the left, enters the superior mediastinum and then ascends to the thoracic inlet along the left border of the oesophagus. In this part of its course the duct is first crossed anteriorly by the aortic arch and it then runs posterior to the left subclavian artery's initial segment, in close contact with the left mediastinal pleura. Passing into the neck it arches laterally at the level of the seventh cervical vertebral transverse process. Its arch rises 3 or 4 cm above the clavicle and curves anterior to the vertebral artery and vein, the left sympathetic trunk, thyrocervical artery or its branches and the left phrenic nerve and medial border of scalenus anterior (but is separated from the nerve and muscle by the prevertebral fascia). The arch passes posterior to: the left common carotid artery, vagus nerve and internal jugular vein. Finally, the duct descends anterior to the arched cervical 'first part' of the left subclavian artery and ends by opening into the junction of the left subclavian and internal jugular veins. However, the duct may open into either of the great veins, near the junction, or it may divide into a number of smaller vessels before terminating (see below).

At its abdominal origin the thoracic duct is about 5 mm in diameter but diminishes in calibre at mid-thoracic levels, then in about 50% of subjects is again slightly dilated before its termination. It is slightly sinuous, constricted at intervals and appears varicose. It may divide in its midcourse into two unequal vessels which soon reunite, or into several small branches which form a plexus before continuing as a single duct. At a higher level it occasionally bifurcates, the left branch ending as usual, the right branch diverging to join one of the right lymph trunks or, when present, a right lymphatic duct; the combined vessel usually opens into the right subclavian vein. The thoracic duct has several valves corresponding to sites exposed to pressure. At its termination a bicuspid valve faces into the vein to prevent or reduce reflux of blood. (After death blood regurgitates freely into the duct, which then looks like a vein.)

Termination

Kinnaert (1973) has collected accounts of 529 dissections (49 his own) of the thoracic duct's termination. In 0–4.5% of subjects no thoracic duct appeared on the left. Multiple terminal openings were frequent (10–40%, according to different observers). In Kinnaert's series the preterminal duct was multiple in 66%, but in only 21% were actual terminal openings multiple. Patterns varied greatly in different studies but, in the two largest by Jdanov (1959) and Kinnaert (1973), sites of termination were respectively 48% and 36% internal jugular vein, 9% and 17% subclavian vein, 35% and 34% jugulosubclavian junction. Termination in the left brachiocephalic (innominate) vein occurred in 8% of Jdanov's series, but never in Kinnaert's.

Lungs

Pulmonary Hila and Roots

The pulmonary root connects the medial surface of the lung to the heart and trachea and is formed by a group of structures entering or leaving the hilum. These are: the principal bronchus, pulmonary artery, two pulmonary veins, bronchial arteries and veins, a pulmonary autonomic plexus, lymph vessels, bronchopulmonary lymph nodes and loose connective tissue, all enveloped by pleura. The pulmonary roots, or pedicles, lie opposite the bodies of the fifth to seventh thoracic vertebrae. The right root is situated behind the superior vena cava and right atrium and below the terminal part of the azygos vein. The left root lies below the aortic arch and in front of the descending thoracic aorta. Common relations of both are: anterior, the phrenic nerve, pericardiophrenic artery and vein, and anterior pulmonary plexus; posterior, the vagus nerve and posterior pulmonary plexus; inferior, the pulmonary ligament.

The major structures in both roots are similarly arranged, as follows: the upper of the two pulmonary veins are in front, the pulmonary artery and principal bronchus are behind, and the bronchial vessels most posterior. Their vertical arrangement differs slightly on the two sides. On the right, from above downwards, the sequence is: superior lobar bronchus, pulmonary artery, principal bronchus, lower pulmonary vein; on the left: pulmonary artery, principal bronchus, the lower pulmonary vein. The lower left pulmonary vein is inferior to the principal bronchus which is the lowest hilar structure.

The different pulmonary regions do not all move equally in respiration. In quiet respiration the juxtahilar part of the lung scarcely moves and the middle region only slightly. The superficial parts of the lung expand the most, while the mediastinal surface, posterior border and apex move less, being related to less movable structures. The diaphragmatic and costomediastinal regions expand most of all. Most of the lung's volumetric change during respiration occurs in the alveoli, which number more than 20 million in a neonatal lung, increasing to 300 million or more during childhood. An alveolus varies from 200–300 μm in diameter and numerous capillary segments (1800 is suggested) may contact each alveolus. The air–epithelium–blood interface is enormous even in childhood. Figures of 70–100 m^2 have been estimated (Peters 1969; Fishman & Pietra 1974) and even higher values have been suggested (Gehr et al 1978).

Pleura: Vessels and nerves

Vessels and Nerves

The parietal and visceral pleurae are developed respectively from somatopleural and splanchnopleural layers of the lateral plate mesoderm. The parietal pleura is therefore supplied by arteries from somatic sources (intercostal, internal thoracic and musculophrenic arteries); its veins join systemic veins in the thoracic wall; its lymphatics also join those in the wall, draining into intercostal, parasternal, posterior mediastinal and diaphragmatic nodes.

Innervation is from spinal sources. The costal and peripheral diaphragmatic pleurae are supplied by intercostal nerves, and the mediastinal and central diaphragmatic pleurae by the phrenic. Irritation of the former results in pain referred along intercostal nerves to the thoracic or abdominal wall; irritation of the latter causes pain referred to the lower neck and shoulder tip, i.e. to the area of skin supplied by the same spinal segments as the phrenic nerve (C 3, 4, 5).

The visceral pleura forms an integral part of the lung; accordingly its arterial supply and venous drainage are provided by the bronchial vessels; its lymphatics join those of the lung (for details see Pennell 1966). Its innervation is autonomic, reaching the visceral pleura along bronchial vessels supplying it. Whereas tactile or thermal stimuli to the parietal pleura elicit pain, these stimuli are inadequate when applied to the visceral pleura (cf. peritoneum).

Peritoneal vessels and nerves

Peritoneal Vessels and Nerves

The parietal and visceral peritoneum are developed from, respectively, the somatopleural and splanchnopleural layers of lateral plate mesoderm. Parietal peritoneum is therefore supplied by somatic blood vessels of the abdominal and pelvic walls; its lymphatics join those in the body wall and drain to parietal lymph nodes; its nerve supply is derived from nerves supplying the muscles and skin of the parietes. Visceral peritoneum, however, as an integral part of the viscera, derives its blood vessels from those supplying viscera. Its lymphatics join the visceral vessels and its nerve supply is autonomic or visceral afferent. Differences in the sensibility of the two layers correlate with their innervations. Whereas pain is elicited by mechanical, thermal or chemical stimulation of the parietal peritoneum, the visceral peritoneum and viscera are not affected; e.g. the liver, stomach or intestine can be injured without evoking pain, insensibility extending from the mid-oesophagus to the junction of endoderm and ectoderm in the anal canal. However, tension does evoke pain when applied to viscera or visceral peritoneum by over-distension or traction on mesenteries, stretching various neural elements in the visceral walls or mesenteries. Also effective are spasms of visceral muscle and ischaemia. Somatic nerves of the parietal peritoneum also supply the corresponding segmental areas of skin and muscles and, when the parietal peritoneum is irritated, muscles are reflexly contracted, causing rigidity of the abdominal wall. The parietal peritoneum on the underside of the diaphragm is supplied with afferent fibres centrally by the **phrenic** nerves and peripherally by the lower six intercostal and subcostal nerves. Hence peripheral irritation may result in pain, tenderness and muscular rigidity in the distribution of the lower thoracic spinal nerves, while central irritation may result in pain in the cutaneous distribution of the third to fifth cervical spinal nerves, i.e. the shoulder region.

Duodenum: Peroneal attachments

Peritoneal Attachments

The superior part of the duodenum is slightly mobile, while the rest is almost fixed, being sessile upon neighbouring structures. Radiologically, after a barium meal, the superior part appears as a triangular, homogeneous shadow, the 'duodenal cap'.

The terminal part and the duodenojejunal flexure are said to be positioned by the 'suspensory muscle of the duodenum' (suspensory muscle, or ligament, of Treitz), often described as being in two parts:

- a slip of skeletal muscle derived from the diaphragm near its oesophageal opening, ending in connective tissue near the coeliac artery
- a fibromuscular band of smooth muscle, passing from the duodenum (third and fourth parts and duodenojejunal flexure) to blend with the same pericoeliac connective tissue.

Treitz (1853) described both entities, naming the former der Hilfsmuskel (the accessory muscle).

Subsequent authorities (Low 1907) regarded them as a digastric muscle, naming the whole the suspensory muscle of Treitz, a misnomer perpetuated in most textbooks. Confusion was increased by Haley & Peden (1943), who derived the 'suspensory muscle' from the right crus, and by Argème et al (1970), who described an intermediate tendon but regarded this as part of a 'false' digastric muscle. Jit (1952, 1977) has persistently repeated the dual nature of the original description by Treitz, supporting it by embryological and histological evidence. The diaphragmatic slip (Hilfsmuskel) has no satisfactory official name. It is supplied, according to Jit, by myelinated nerve fibres probably from the **phrenic** nerve (pp. 816, 1265) and is sometimes considered an aberrant part of iliocostalis thoracis. The suspensory muscle proper (smooth muscle) is supplied by autonomic fibres from the coeliac and superior mesenteric plexuses (Jit & Grewal 1977). Descriptions of the duodenal attachments of the muscle vary; none of these accounts contain a convincing view of its function, the usual suggestion being that it augments duodenojejunal flexure, acting like a valve.

Bile duct

The bile duct is formed near the porta hepatis, by the junction of the cystic and common hepatic ducts; it is usually about 7.5 cm long and 6 mm in diameter. It descends posteriorly and slightly to the left, anterior to the epiploic foramen, at the right border of the lesser omentum, in front and to the right of the portal vein and to the right of the hepatic artery proper. It passes behind the first (superior) part of the duodenum, with the gastroduodenal artery on its left, and then runs in a groove on the superolateral part of the posterior surface of the head of the pancreas, anterior to the inferior vena cava and sometimes embedded in pancreatic tissue. Lytle (1959) has shown that the duct may be close to the left aspect of the second (descending) part of the duodenum or as much as 2 cm from it

and that, even when it is embedded in pancreas, a superficial groove marking its position can be palpated behind the descending part of the duodenum, stones in the duct being thus detected. Left of the descending part of the duodenum the bile duct reaches the pancreatic duct; together they enter the duodenal wall where they usually unite to form the hepatopancreatic ampulla (p. 1791), the distal, constricted end of which opens into the descending part of the duodenum on the summit of the major duodenal papilla, about 8–10 cm from the pylorus. The position of the bile duct is indicated on the anterior abdominal surface by a line starting 5 cm above the transpyloric plane and 2 cm right of the median plane and descending vertically for 7.5 cm.

Vessels

The cystic artery is described on page 1550 and the cystic veins on page 1604. The lower part of the bile duct receives rami from the posterior superior pancreaticoduodenal artery, while its upper part and the hepatic ducts receive rami from the cystic artery. The right hepatic artery supplies its intermediate part through very small rami, the main supply being from the cystic and posterior superior pancreaticoduodenal arteries. These supplies vary (Shapiro & Robillard 1948; Michels 1962). The posterior superior pancreaticoduodenal artery anastomoses with the posterior branch of the inferior pancreaticoduodenal near the hepatopancreatic ampulla; where this anastomosis is poor, ligation of the posterior superior pancreaticoduodenal artery may result in gangrene or stricture of the bile duct (Henley 1955). Veins from the upper part of the bile duct and hepatic ducts and from the gallbladder and cystic duct usually enter the liver, while those from the lower part of the bile duct enter the portal vein. Lymph vessels of the gallbladder and bile ducts are described on page 1619. Sympathetic and parasympathetic innervation is from the coeliac plexus along the hepatic artery and its branches. Autonomic plexuses exist in the muscular and submucous layers, and ganglion cells, presumably parasympathetic, have been demonstrated in these plexuses in monkeys (Sutherland 1966, 1967). Fibres from the right **phrenic** nerve, through communications between the **phrenic** and coeliac plexuses, appear to reach the gallbladder via the hepatic plexus, thus explaining referred 'shoulder pain' in gallbladder pathology.