CHAPTER 7

The nervous system

ANIMATIONS

The nervous system detects and responds to changes inside and outside the body. Together with the endocrine system, it coordinates and controls vital aspects of body function and maintains homeostasis. To this end the nervous system provides an immediate response while endocrine activity (Ch. 9) is, usually, slower and more prolonged.

The nervous system consists of the brain, the spinal cord and peripheral nerves (see Fig. 1.10, p. 10). The structure and organisation of the tissues that form these components enables rapid communication between all parts of the body.

For descriptive purposes the parts of the nervous system are grouped as follows:

- the *central nervous system* (CNS), consisting of the brain and the spinal cord
- the *peripheral nervous system* (PNS), consisting of all the nerves outside the brain and spinal cord. **7.1**

The PNS comprises paired cranial and sacral nerves – some of these are sensory (afferent) transmitting impulses to the CNS, some are motor (efferent) transmitting impulses from the CNS and others are mixed. It is useful to consider two functional parts within the PNS:

- the sensory division
- the motor division (Fig. 7.1).

The motor division has two parts:

- the *somatic nervous system*, which controls voluntary movement of skeletal muscles
- the *autonomic nervous system*, controlling involuntary processes such as heartbeat, peristalsis (p. 289) and glandular activity. The autonomic nervous system has two divisions: *sympathetic* and *parasympathetic*.

In summary, the CNS receives sensory information about its internal and external environments from afferent nerves. The CNS integrates and processes this input and responds, when appropriate, by sending nerve impulses through motor nerves to the effector organs: muscles and glands. For example, responses to changes in the internal environment regulate essential involuntary body functions such as respiration and blood pressure; responses to changes in the external environment maintain posture and other voluntary activities.

The first sections of this chapter explore the structure and functions of the components of the nervous system including the impact of ageing, while the final one considers the effects on body function when its structures do not function normally.

Cells and tissues of the nervous system

Learning outcomes

After studying this section, you should be able to:

- compare and contrast the structure and functions of myelinated and unmyelinated neurones
- state the functions of sensory and motor nerves
- explain the events that occur following release of a neurotransmitter at a synapse
- briefly describe the functions of four types of neuroglial cells
- outline the response of nervous tissue to injury.

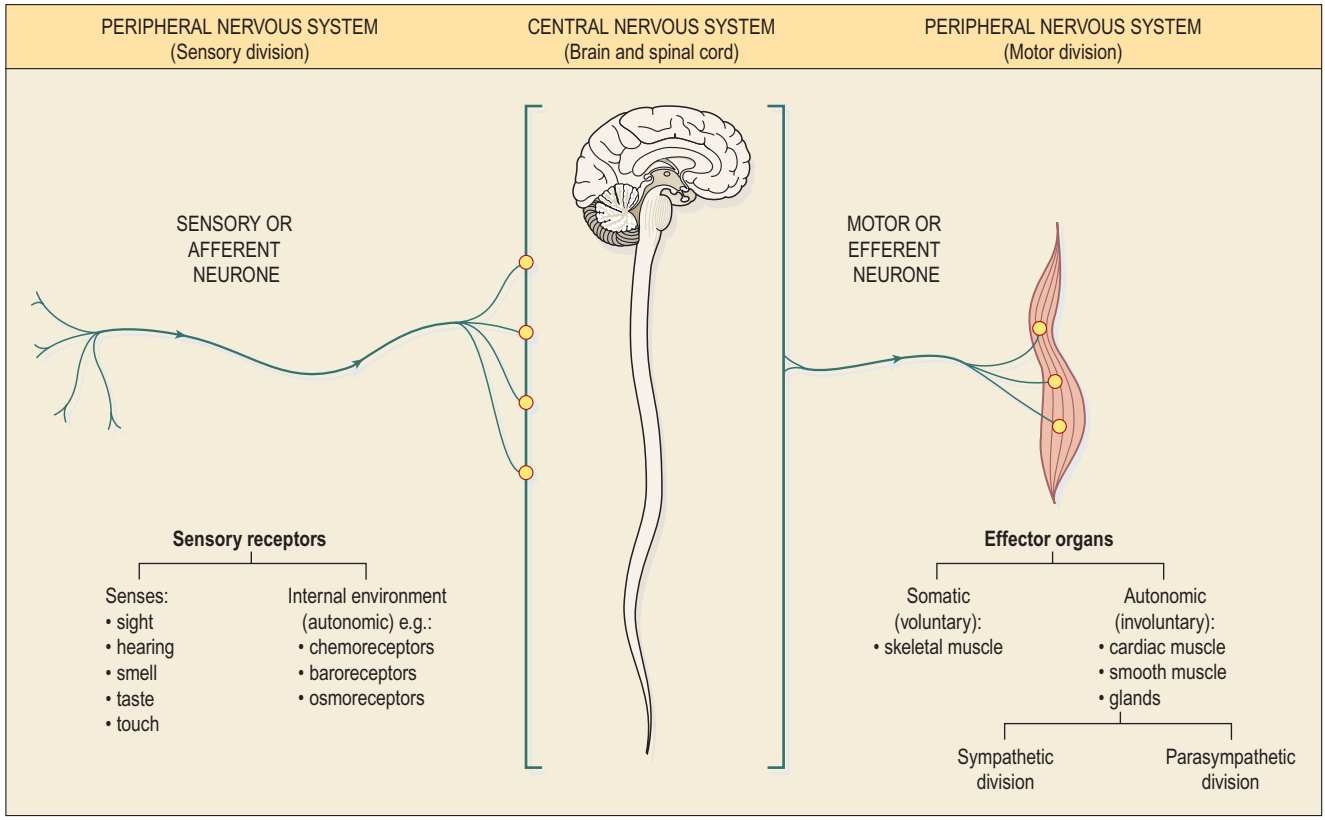

Figure 7.1 Functional components of the nervous system.

There are two types of nervous tissue, neurones and neuroglia. *Neurones* (nerve cells) are the working units of the nervous system that generate and transmit *nerve impulses*. Neurones are supported by connective tissue, collectively known as *neuroglia*, which is formed from different types of *glial cells*. There are vast numbers of both cell types, 1 trillion (10^{12}) glial cells and 10 times fewer (10^{11}) neurones.

Neurones (Fig. 7.2) 7.2

Each neurone (Fig. 7.2) consists of a *cell body* and its processes, one *axon* and many *dendrites*. Neurones are commonly referred to as nerve cells. Bundles of axons bound together are called *nerves*. Neurones cannot divide, and for survival they need a continuous supply of oxygen and glucose. Unlike many other cells, neurones can synthesise chemical energy (ATP) only from glucose.

Neurones generate and transmit electrical impulses called *action potentials*. The initial strength of the impulse is maintained throughout the length of the neurone. Some neurones initiate nerve impulses while others act as 'relay stations' where impulses are passed on and sometimes redirected.

Nerve impulses can be initiated in response to stimuli from:

- outside the body, e.g. touch, light waves
- inside the body, e.g. a change in the concentration of carbon dioxide in the blood alters respiration; a thought may result in voluntary movement.

Transmission of nerve signals is both electrical and chemical. The action potential travelling down the nerve axon is an electrical signal, but because nerves do not come into direct contact with each other, the signal between a nerve cell and the next cell in the chain is nearly always chemical (p. 148).

Cell bodies

Nerve cells vary considerably in size and shape but they are all too small to be seen by the naked eye. Cell bodies form the *grey matter* of the nervous system and are found at the periphery of the brain and in the centre of the spinal cord. Groups of cell bodies are called *nuclei* in the central nervous system and *ganglia* in the peripheral nervous system. An important exception is the basal ganglia (nuclei) situated within the cerebrum (p. 156).

Axons and dendrites

Axons and dendrites are extensions of cell bodies and form the *white matter* of the nervous system. Axons are

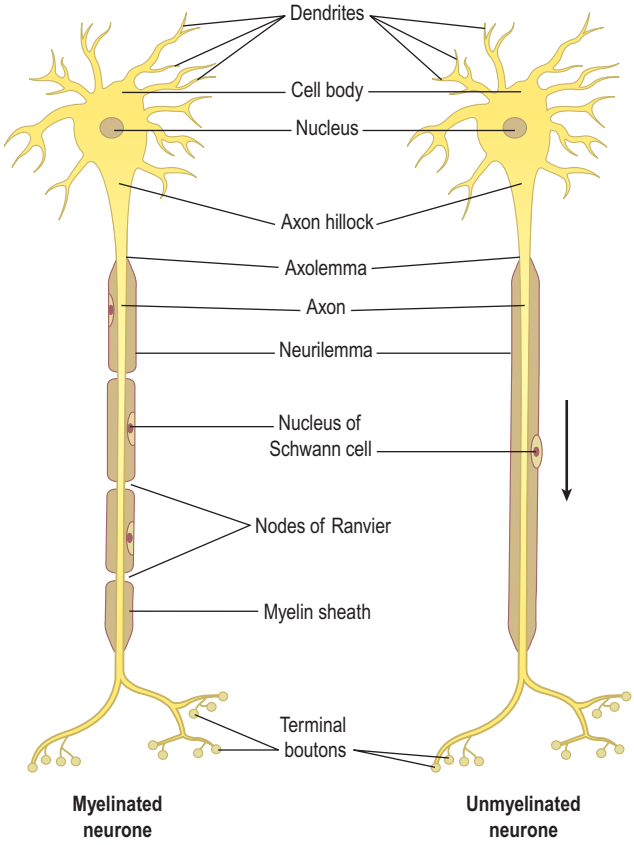

Figure 7.2 The structure of neurones. Arrow indicates direction of impulse conduction.

found deep in the brain and in groups, called *tracts*, at the periphery of the spinal cord. They are referred to as *nerves* or *nerve fibres* outside the brain and spinal cord.

Axons

Each nerve cell has only one axon, which begins at a tapered area of the cell body, the *axon hillock*. They carry impulses away from the cell body and are usually longer than the dendrites, sometimes as long as 100 cm.

Structure of an axon. The membrane of the axon is called the *axolemma* and it encloses the cytoplasmic extension of the cell body.

Myelinated neurones Large axons and those of peripheral nerves are surrounded by a *myelin sheath* (Figs 7.3A and C). This consists of a series of *Schwann cells* arranged along the length of the axon. Each one is wrapped around the axon so that it is covered by a number of concentric layers of Schwann cell plasma membrane. Between the layers of plasma membrane is a small amount of fatty substance called *myelin*. The outermost layer of the Schwann cell plasma membrane is the *neurilemma*. There are tiny areas of exposed axolemma between adjacent Schwann cells, called *nodes of Ranvier* (Fig. 7.2), which assist the rapid transmission of nerve impulses in myelinated neurones. Figure 7.4 shows a section through a nerve fibre at a node of Ranvier where the area without myelin can be clearly seen.

Unmyelinated neurones Postganglionic fibres and some small fibres in the central nervous system are *unmyelinated*. In this type a number of axons are embedded in one Schwann cell (Fig. 7.3B). The adjacent Schwann cells are in close association and there is no

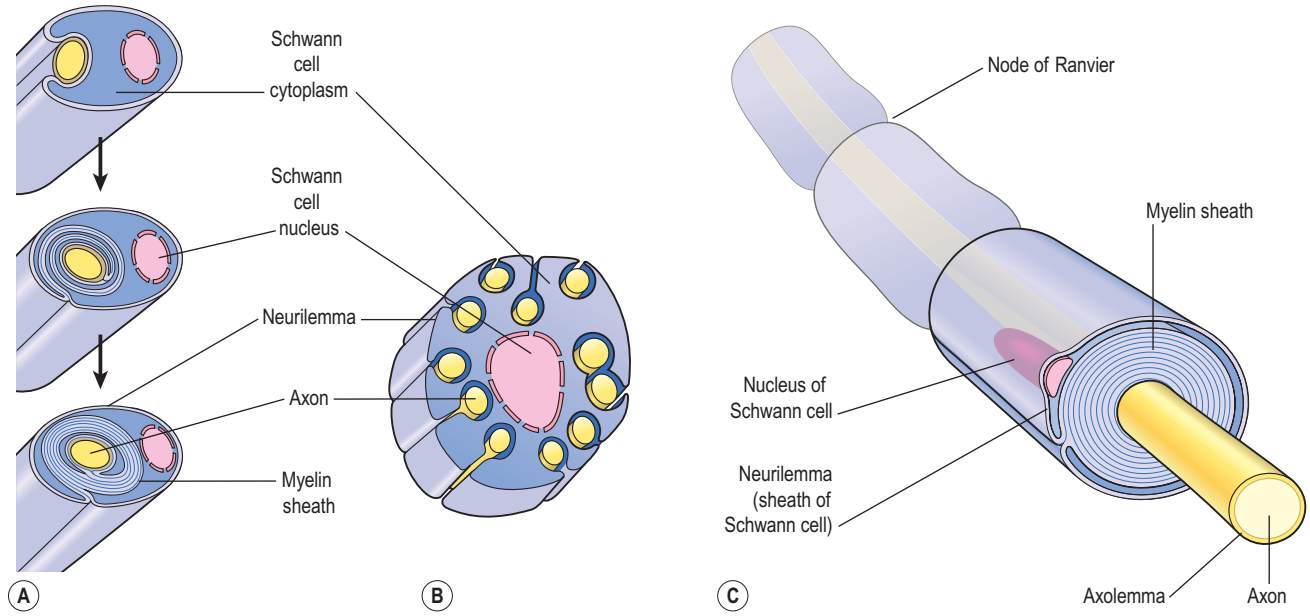

Figure 7.3 Arrangement of myelin. A. Myelinated neurone. **B.** Unmyelinated neurone. **C.** Length of myelinated axon.

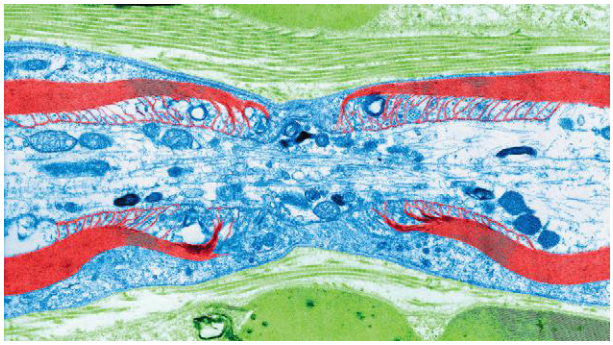

Figure 7.4 Node of Ranvier. A colour transmission electron micrograph of a longitudinal section of a myelinated nerve fibre. Nerve tissue is shown in blue and myelin in red.

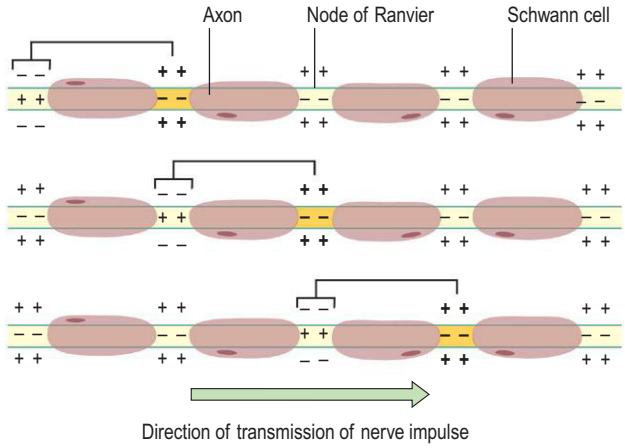

Figure 7.5 Saltatory conduction of an impulse in a myelinated nerve fibre.

exposed axolemma. The speed of transmission of nerve impulses is significantly slower in unmyelinated fibres.

Dendrites

These are the many short processes that receive and carry incoming impulses towards cell bodies. They have the same structure as axons but are usually shorter and branching. In motor neurones dendrites form part of synapses (see Fig. 7.7) and in sensory neurones they form the sensory receptors that respond to specific stimuli.

The nerve impulse (action potential) 7.3

An impulse is initiated by stimulation of sensory nerve endings or by the passage of an impulse from another nerve. Transmission of the impulse, or action potential, is due to movement of ions across the nerve cell membrane. In the resting state the nerve cell membrane is *polarised* due to differences in the concentrations of ions across the plasma membrane. This means that there is a different electrical charge on each side of the membrane, which is called the *resting membrane potential*. At rest the charge on the outside is positive and inside it is negative. The principal ions involved are:

- sodium (Na^+), the main extracellular cation
- potassium (K^+), the main intracellular cation.

In the resting state there is a continual tendency for these ions to diffuse along their concentration gradients, i.e. K^+ outwards and Na^+ into cells. When stimulated, the permeability of the nerve cell membrane to these ions changes. Initially Na^+ floods into the neurone from the extracellular fluid causing *depolarisation*, creating a *nerve impulse* or *action potential*. Depolarisation is very rapid, enabling the conduction of a nerve impulse along the entire length of a neurone in a few milliseconds. It passes from the point of stimulation in one direction only, i.e. away from the point of stimulation towards the area of resting potential. The one-way direction of transmission is ensured because following depolarisation it takes time for *repolarisation* to occur.

Almost immediately following the entry of Na^+, K^+ floods out of the neurone and the movement of these ions returns the membrane potential to its resting state. This is called the *refractory period* during which restimulation is not possible. The action of the *sodium–potassium pump* expels Na^+ from the cell in exchange for K^+ (see p. 37) returning levels of Na^+ and K^+ to the original resting state, repolarizing the neurone.

In myelinated neurones, the insulating properties of the myelin sheath prevent the movement of ions. Therefore electrical changes across the membrane can only occur at the gaps in the myelin sheath, i.e. at the nodes of Ranvier (see Fig. 7.2). When an impulse occurs at one node, depolarisation passes along the myelin sheath to the next node so that the flow of current appears to 'leap' from one node to the next. This is called *saltatory conduction* (Fig. 7.5).

The speed of conduction depends on the diameter of the neurone: the larger the diameter, the faster the conduction. In addition, myelinated fibres conduct impulses faster than unmyelinated fibres because saltatory conduction is faster than continuous conduction, or *simple propagation* (Fig. 7.6). The fastest fibres can conduct impulses to, e.g., skeletal muscles at a rate of 130 metres per second while the slowest impulses travel at 0.5 metres per second.

The synapse and neurotransmitters 7.4

There is always more than one neurone involved in the transmission of a nerve impulse from its origin to its destination, whether it is sensory or motor. There is no physical contact between two neurones. The point at which the nerve impulse passes from the *presynaptic neurone* to the *postsynaptic neurone* is the *synapse* (Fig. 7.7). At its free end, the axon of the presynaptic neurone breaks up into minute branches that terminate in small swellings called *synaptic knobs*, or terminal boutons. These are in close proximity to the dendrites and the cell body of the

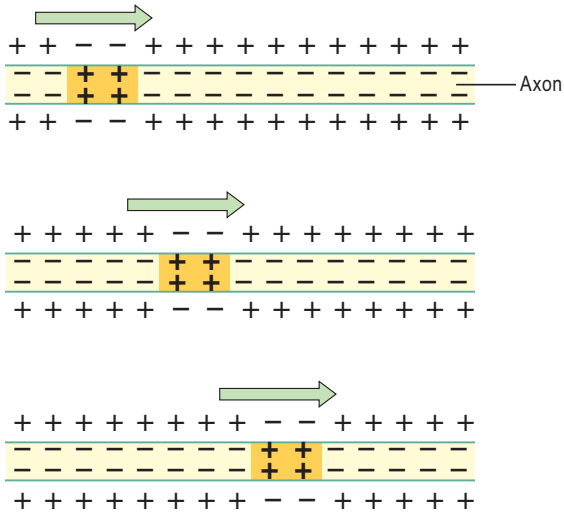

Figure 7.6 Simple propagation of an impulse in an unmyelinated nerve fibre. Arrows indicate the direction of impulse transmission.

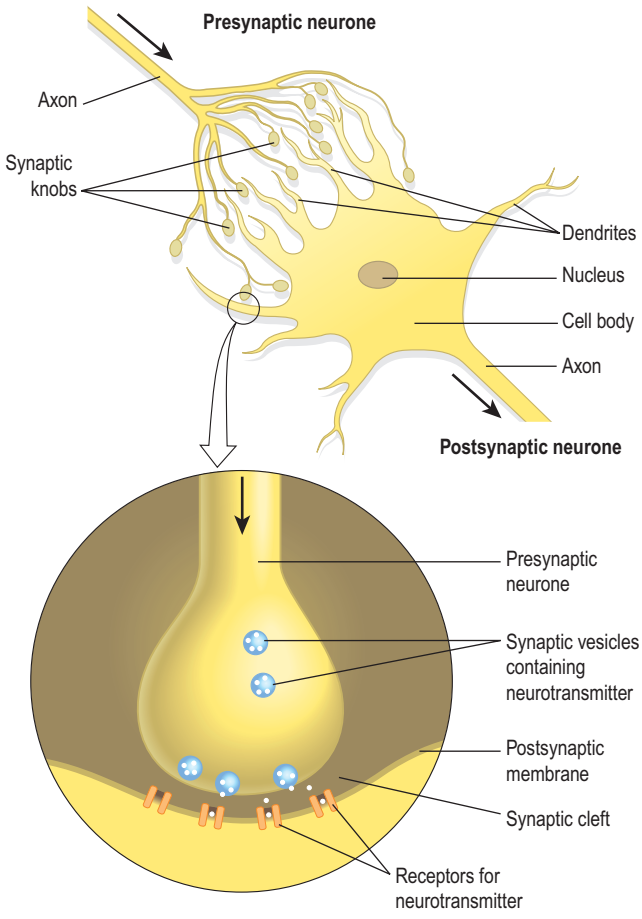

Figure 7.7 Diagram of a synapse. Arrows show direction of nerve impulse.

postsynaptic neurone. The space between them is the *synaptic cleft*. Synaptic knobs contain spherical membrane bound *synaptic vesicles*, which store a chemical, the *neurotransmitter* that is released into the synaptic cleft. Neurotransmitters are synthesised by nerve cell bodies, actively transported along the axons and stored in the synaptic vesicles. They are released by exocytosis in response to the action potential and diffuse across the synaptic cleft. They act on specific receptor sites on the postsynaptic membrane. Their action is short lived, because immediately they have acted on the postsynaptic cell such as a muscle fibre, they are either inactivated by enzymes or taken back into the synaptic knob. Some important drugs mimic, neutralise (antagonise) or prolong neurotransmitter activity. Neurotransmitters usually have an excitatory effect on postsynaptic receptors but they are sometimes inhibitory.

There are more than 50 neurotransmitters in the brain and spinal cord including noradrenaline (norepinephrine), adrenaline (epinephrine), dopamine, histamine, serotonin, gamma aminobutyric acid (GABA) and acetylcholine. Other substances, such as enkephalins, endorphins and substance P, have specialised roles in, for example, transmission of pain signals. Figure 7.8 summarises the main neurotransmitters of the peripheral nervous system.

Somatic nerves carry impulses directly to the synapses at skeletal muscles, the *neuromuscular junctions* (p. 422) stimulating contraction. In the autonomic nervous system (see p. 173), efferent impulses travel along two neurones (preganglionic and postganglionic) and across two synapses to the effector tissue, i.e. cardiac muscle, smooth muscle and glands, in both the sympathetic and the parasympathetic divisions.

Nerves

A nerve consists of numerous neurones collected into bundles (bundles of nerve fibres in the central nervous system are known as *tracts*). For example large nerves such as the sciatic nerves (p. 169) contain tens of thousands of axons. Each bundle has several coverings of protective connective tissue (Fig. 7.9):

- *endoneurium* is a delicate tissue, surrounding each individual fibre, which is continuous with the septa that pass inwards from the perineurium
- *perineurium* is a smooth connective tissue, surrounding each *bundle* of fibres
- *epineurium* is the fibrous tissue which surrounds and encloses a number of bundles of nerve fibres. Most large nerves are covered by epineurium.

Sensory or afferent nerves

Sensory nerves carry information from the body to the spinal cord (Fig. 7.1). The impulses may then pass to the

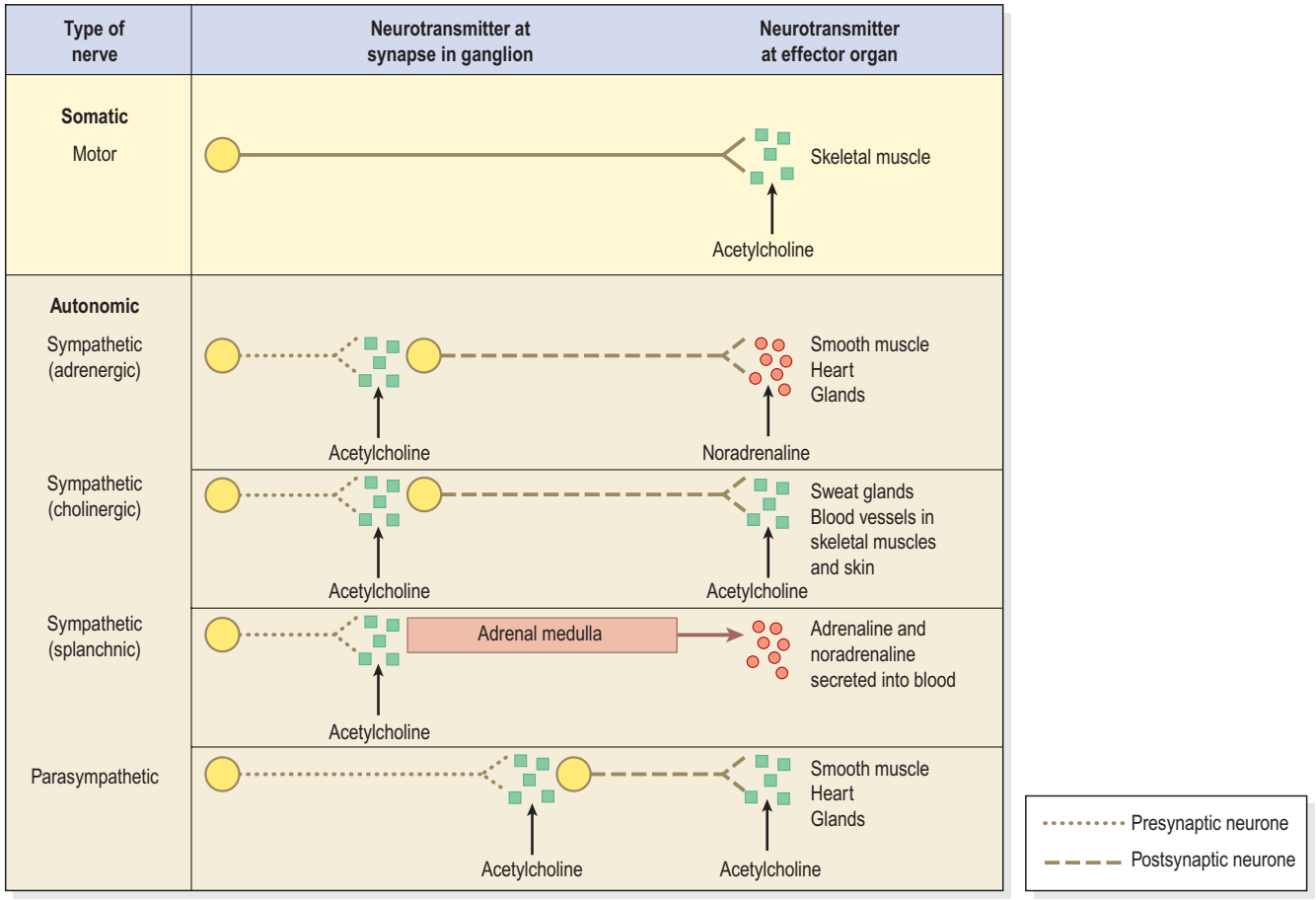

Figure 7.8 Main neurotransmitters at synapses in the peripheral nervous system.

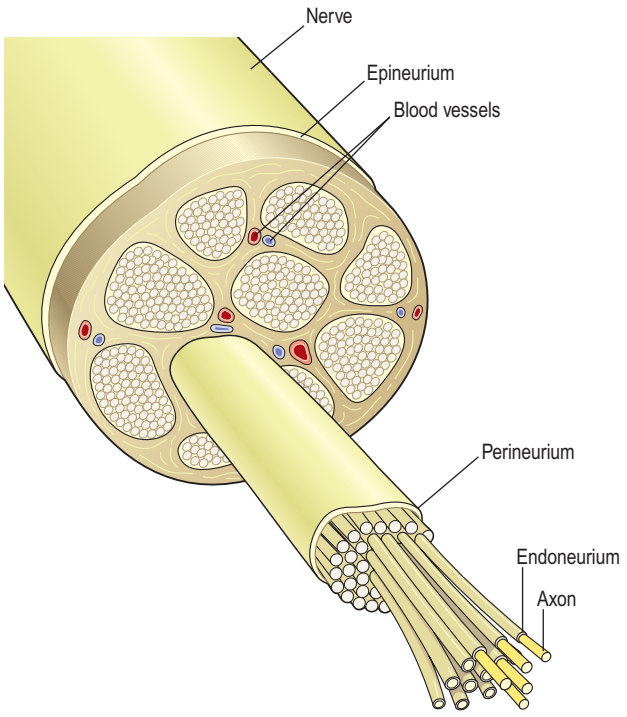

Figure 7.9 Transverse section of a peripheral nerve showing the protective connective tissue coverings.

brain or to connector neurones of reflex arcs in the spinal cord (see p. 164).

Sensory receptors

Specialised endings of sensory neurones respond to different stimuli (changes) inside and outside the body.

Somatic, cutaneous or common senses. These originate from the skin. They are: pain, touch, heat and cold. Sensory nerve endings in the skin are fine branching filaments without myelin sheaths (see Fig. 14.4, p. 364). When stimulated, an impulse is generated and transmitted by the sensory nerves to the brain where the sensation is perceived.

Proprioceptor senses. These originate in muscles and joints. Impulses sent to the brain enable perception of the position of the body and its parts in space maintaining posture and balance (see Ch. 16).

Special senses. These are sight, hearing, balance, smell and taste (see Ch. 8).

Autonomic afferent nerves. These originate in internal organs, glands and tissues, e.g. baroreceptors involved in the control of blood pressure (Ch. 5), chemoreceptors involved in the control of respiration (Ch. 10), and are

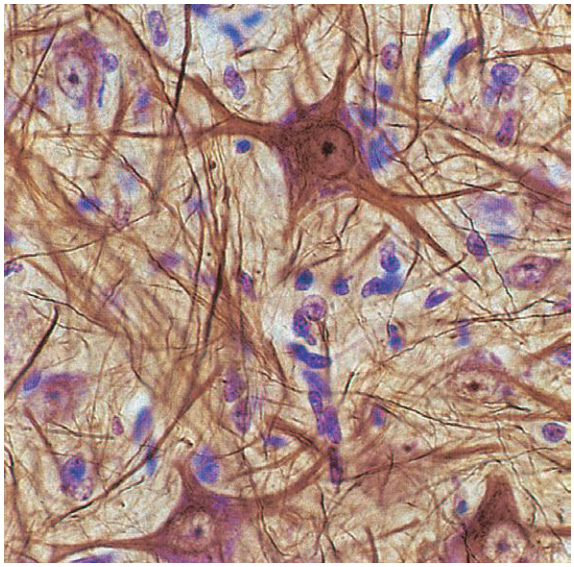

Figure 7.10 Neurones and glial cells. A stained light micrograph of neurones (gold) and nuclei of the more numerous glial cells (blue).

associated with reflex regulation of involuntary activity and visceral pain.

Motor or efferent nerves

Motor nerves originate in the brain, spinal cord and autonomic ganglia. They transmit impulses to the effector organs: muscles and glands (Fig. 7.1). There are two types:

- *somatic nerves* – involved in voluntary and reflex skeletal muscle contraction
- *autonomic nerves* (sympathetic and parasympathetic) – involved in cardiac and smooth muscle contraction and glandular secretion.

Mixed nerves

In the spinal cord, sensory and motor nerves are arranged in separate groups, or *tracts*. Outside the spinal cord, when sensory and motor nerves are enclosed within the same sheath of connective tissue they are called *mixed nerves*.

Neuroglia

The neurones of the central nervous system are supported by non-excitable *glial cells* that greatly outnumber the neurones (Fig. 7.10). Unlike nerve cells, which cannot divide, glial cells continue to replicate throughout life. There are four types: *astrocytes, oligodendrocytes, ependymal cells* and *microglia*.

Astrocytes

These cells form the main supporting tissue of the central nervous system (Fig. 7.11). They are star shaped with

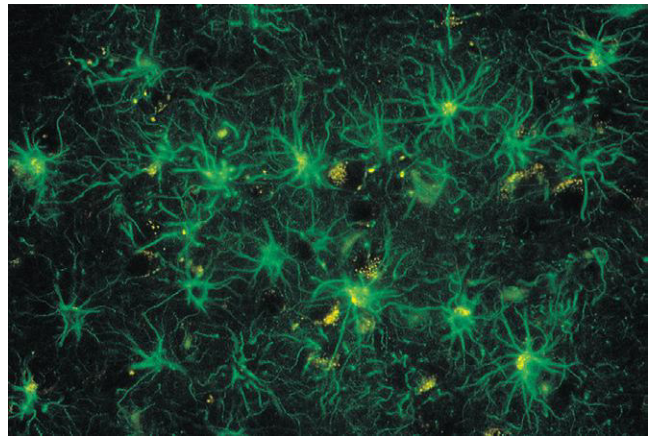

Figure 7.11 Star-shaped astrocytes in the cerebral cortex.

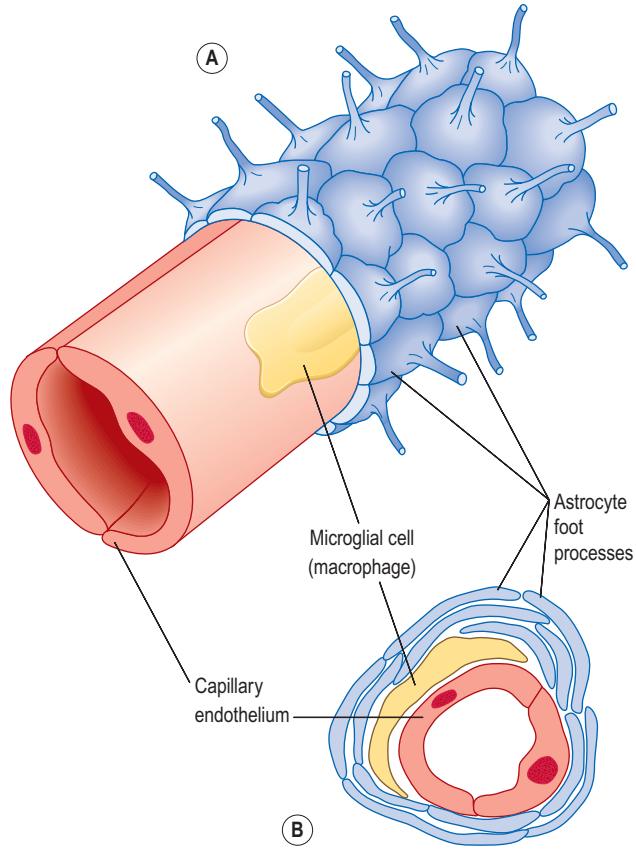

Figure 7.12 Blood–brain barrier. A. Longitudinal section. **B.** Transverse section.

fine branching processes and they lie in a mucopolysaccharide ground substance. At the free ends of some of the processes are small swellings called *foot processes*. Astrocytes are found in large numbers adjacent to blood vessels with their foot processes forming a sleeve round them. This means that the blood is separated from the neurones by the capillary wall and a layer of astrocyte foot processes which together constitute the *blood–brain barrier* (Fig. 7.12).

The blood–brain barrier is a selective barrier that protects the brain from potentially toxic substances and chemical variations in the blood, e.g. after a meal. Oxygen, carbon dioxide, glucose and other lipid-soluble substances, e.g. alcohol, quickly cross the barrier into the brain. Some large molecules, many drugs, inorganic ions and amino acids pass more slowly, if at all, from the blood to the brain.

Oligodendrocytes

These cells are smaller than astrocytes and are found in clusters round nerve cell bodies in grey matter, where they are thought to have a supportive function. They are found adjacent to, and along the length of, myelinated nerve fibres. Oligodendrocytes form and maintain myelin like Schwann cells in peripheral nerves.

Ependymal cells

These cells form the epithelial lining of the ventricles of the brain and the central canal of the spinal cord. Those cells that form the choroid plexuses of the ventricles secrete cerebrospinal fluid.

Microglia

The smallest and least numerous glial cells, these cells may be derived from monocytes that migrate from the blood into the nervous system before birth. They are found mainly in the area of blood vessels. They enlarge and become phagocytic, removing microbes and damaged tissue, in areas of inflammation and cell destruction.

Response of nervous tissue to injury

Neurones reach maturity a few weeks after birth and cannot be replaced.

Damage to neurones can either lead to rapid necrosis with sudden acute functional failure, or to slow atrophy with gradually increasing dysfunction. These changes are associated with:

- hypoxia and anoxia
- nutritional deficiencies
- poisons, e.g. organic lead
- trauma
- infections
- ageing
- hypoglycaemia.

Peripheral nerve regeneration (Fig. 7.13)

The axons of *peripheral nerves* can sometimes regenerate if the cell body remains intact. Distal to the damage, the axon and myelin sheath disintegrate and are removed by macrophages; the muscle supplied by the damaged fibre atrophies in the absence of nerve stimulation. The neurilemma then regenerates (about 1.5 mm per day) from the point of injury towards the effector along its original track provided the two parts of the neurilemma are in close apposition (Fig. 7.13A). New Schwann cells develop within the neurilemma providing a pathway within which the axon can regenerate.

Restoration of function depends on the re-establishment of satisfactory neural connections with the effector organ. When the neurilemma is out of position or destroyed, the sprouting axons and Schwann cells form a tumour-like cluster (*traumatic neuroma*) producing severe pain, e.g. following some fractures and amputation of limbs (Fig. 7.13B).

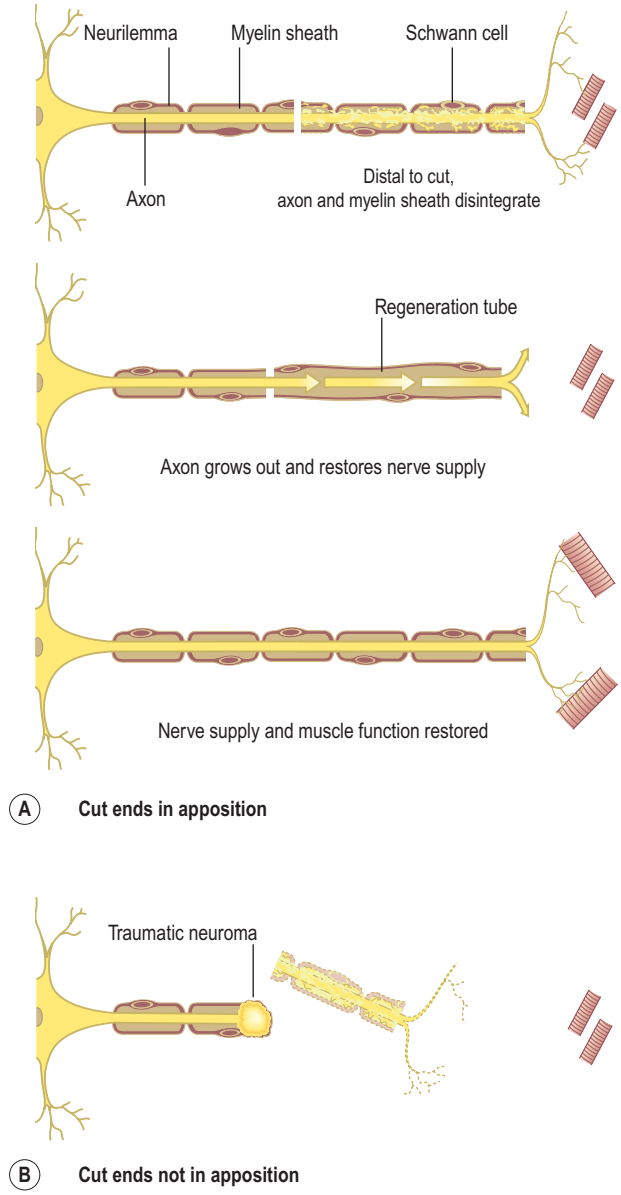

Figure 7.13 Regrowth of peripheral nerves following injury.

Neuroglial damage

Astrocytes. When these cells are damaged, their processes multiply forming a mesh or 'scar', which is thought to inhibit the regrowth of damaged CNS neurones.

Oligodendrocytes. These cells increase in number around degenerating neurones and are destroyed in demyelinating diseases such as *multiple sclerosis* (p. 185).

Microglia. Where there is inflammation and cell destruction the microglia increase in size and become phagocytic.

Central nervous system

The central nervous system consists of the brain and the spinal cord (see Fig. 7.1). These essential structures are both well protected from damage and injury; the brain is enclosed within the skull and the spinal cord by the vertebrae that form the spinal column. Membranous coverings known as the *meninges* provide further protection. The structure and functions of the meninges, brain and spinal cord are explored in this section.

The meninges and cerebrospinal fluid (CSF)

Learning outcomes

After studying this section, you should be able to:

- describe the structure of the meninges
- describe the flow of cerebrospinal fluid in the brain
- list the functions of cerebrospinal fluid.

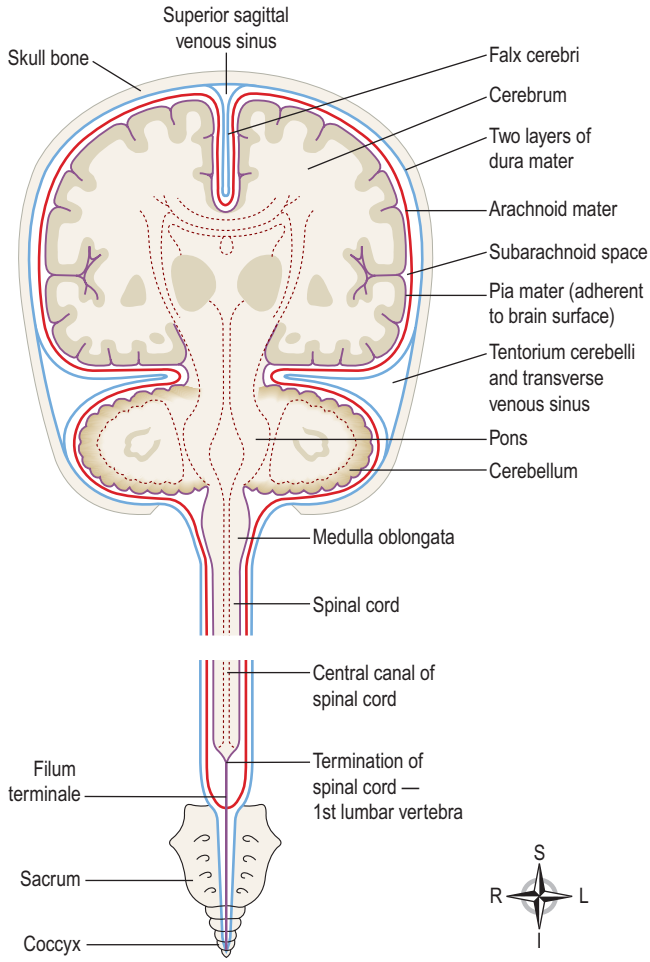

Figure 7.14 Frontal section showing the meninges covering the brain and spinal cord.

The meninges (Fig. 7.14)

The brain and spinal cord are completely surrounded by three layers of tissue, the *meninges*, lying between the skull and the brain, and between the vertebral foramina and the spinal cord. Named from outside inwards they are the:

- dura mater
- arachnoid mater
- pia mater.

The dura and arachnoid maters are separated by a potential space, the *subdural space*. The arachnoid and pia maters are separated by the *subarachnoid space*, containing *cerebrospinal fluid*.

Dura mater

The cerebral dura mater consists of two layers of dense fibrous tissue. The outer layer takes the place of the periosteum on the inner surface of the skull bones and the inner layer provides a protective covering for the brain. There is only a potential space between the two layers except where the inner layer sweeps inwards between the cerebral hemispheres to form the *falx cerebri*; between the cerebellar hemispheres to form the *falx cerebelli*; and between the cerebrum and cerebellum to form the *tentorium cerebelli*.

Venous blood from the brain drains into venous sinuses between the two layers of dura mater. The *superior sagittal sinus* is formed by the falx cerebri, and the tentorium cerebelli forms the *straight* and *transverse sinuses* (see Figs 5.34 and 5.35, p. 106).

Spinal dura mater forms a loose sheath round the spinal cord, extending from the foramen magnum to the 2nd sacral vertebra. Thereafter it encloses the *filum terminale* and fuses with the periosteum of the coccyx. It is an extension of the inner layer of cerebral dura mater and is separated from the periosteum of the vertebrae and ligaments within the neural canal by the *epidural space* (see Fig. 7.26), containing blood vessels and areolar connective tissue. It is attached to the foramen magnum and by strands of fibrous tissue to the posterior longitudinal ligament at intervals along its length. Nerves entering and leaving the spinal cord pass through the

epidural space. These attachments stabilise the spinal cord in the neural canal. Dyes, used for diagnostic purposes, and local anaesthetics or analgesics to relieve pain, may be injected into the epidural space.

Arachnoid mater

This is a layer of fibrous tissue that lies between the dura and pia maters. It is separated from the dura mater by the *subdural space* that contains a small amount of serous fluid, and from the pia mater by the *subarachnoid space*, which contains *cerebrospinal fluid*. The arachnoid mater passes over the convolutions of the brain and accompanies the inner layer of dura mater in the formation of the falx cerebri, tentorium cerebelli and falx cerebelli. It continues downwards to envelop the spinal cord and ends by merging with the dura mater at the level of the 2nd sacral vertebra.

Pia mater

This is a delicate layer of connective tissue containing many minute blood vessels. It adheres to the brain, completely covering the convolutions and dipping into each fissure. It continues downwards surrounding the spinal cord. Beyond the end of the cord it continues as the *filum terminale*, pierces the arachnoid tube and goes on, with the dura mater, to fuse with the periosteum of the coccyx.

Ventricles of the brain and the cerebrospinal fluid 7.5

The brain contains four irregular-shaped cavities, or *ventricles*, containing cerebrospinal fluid (CSF) (Fig. 7.15). They are:

- right and left lateral ventricles
- third ventricle
- fourth ventricle.

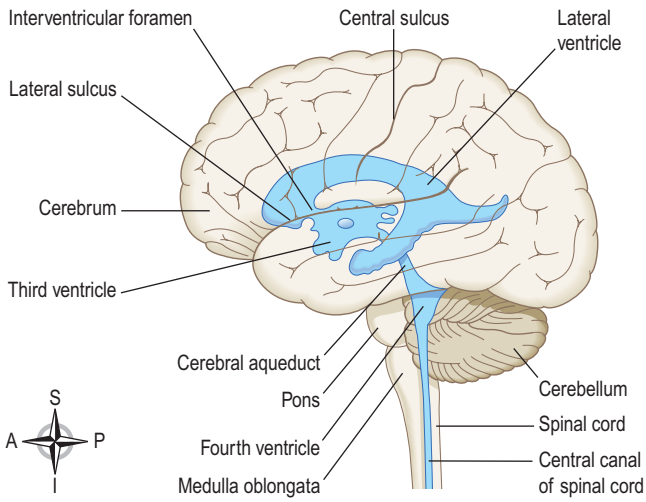

Figure 7.15 The positions of the ventricles of the brain (in blue) superimposed on its surface. Viewed from the left side.

The lateral ventricles

These cavities lie within the cerebral hemispheres, one on each side of the median plane just below the corpus callosum. They are separated from each other by a thin membrane, the septum lucidum, and are lined with ciliated epithelium. They communicate with the third ventricle by *interventricular foramina*.

The third ventricle

The third ventricle is a cavity situated below the lateral ventricles between the two parts of the thalamus. It communicates with the fourth ventricle by a canal, the *cerebral aqueduct*.

The fourth ventricle

The fourth ventricle is a diamond-shaped cavity situated below and behind the third ventricle, between the *cerebellum* and *pons*. It is continuous below with the *central canal* of the spinal cord and communicates with the subarachnoid space by foramina in its roof. Cerebrospinal fluid enters the subarachnoid space through these openings and through the open distal end of the central canal of the spinal cord.

Cerebrospinal fluid (CSF)

Cerebrospinal fluid is secreted into each ventricle of the brain by *choroid plexuses*. These are vascular areas where there is a proliferation of blood vessels surrounded by ependymal cells in the lining of ventricle walls. CSF passes back into the blood through tiny diverticula of arachnoid mater, called *arachnoid villi* (arachnoid granulations, Fig. 7.16), which project into the venous sinuses. The movement of CSF from the subarachnoid space to venous sinuses depends upon the difference in pressure on each side of the walls of the arachnoid villi, which act as one-way valves. When CSF pressure is higher than venous pressure, CSF is pushed into the blood and when the venous pressure is higher the arachnoid villi collapse, preventing the passage of blood constituents into the CSF. There may also be some reabsorption of CSF by cells in the walls of the ventricles.

From the roof of the fourth ventricle CSF flows through foramina into the subarachnoid space and completely surrounds the brain and spinal cord (Fig. 7.16). There is no intrinsic system of CSF circulation but its movement is aided by pulsating blood vessels, respiration and changes of posture.

CSF is secreted continuously at a rate of about 0.5 mL per minute, i.e. 720 mL per day. The volume remains fairly constant at about 150 mL, as absorption keeps pace with secretion. CSF pressure may be measured using a vertical tube attached to a *lumbar puncture* needle inserted into the subarachnoid space above or below the 4th lumbar vertebra (which is below the end of

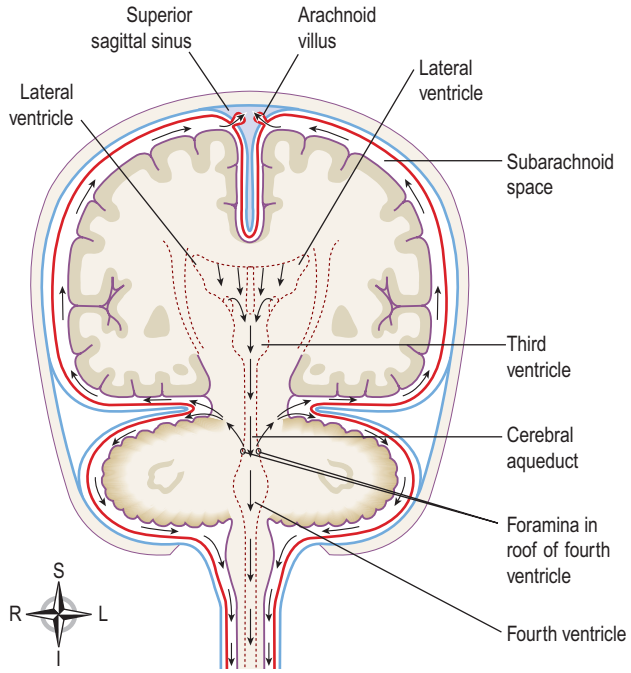

Figure 7.16 Frontal section of the skull with arrows showing the flow of cerebrospinal fluid.

the spinal cord). The pressure remains fairly constant at about 10 cm H_2O when lying on one side and about 30 cm H_2O when sitting up. If the brain is enlarged by, e.g., haemorrhage or tumour, some compensation is made by a reduction in the amount of CSF. When the volume of brain tissue is reduced, such as in degeneration or atrophy, the volume of CSF is increased. CSF is a clear, slightly alkaline fluid with a specific gravity of 1.005, consisting of:

- water
- mineral salts
- glucose
- plasma proteins: small amounts of albumin and globulin
- a few leukocytes
- creatinine, urea } small amounts

Functions of cerebrospinal fluid

CSF supports and protects the brain and spinal cord by maintaining a uniform pressure around these vital structures and acting as a cushion or shock absorber between the brain and the skull.

It keeps the brain and spinal cord moist and there may be exchange of nutrients and waste products between CSF and the interstitial fluid of the brain. CSF is thought to be involved in regulation of breathing as it bathes the surface of the medulla where the central respiratory chemoreceptors are located (Ch. 10).

Brain

Learning outcomes

After studying this section, you should be able to:

- describe the blood supply to the brain
- name the lobes and principal sulci of the brain
- outline the functions of the cerebrum
- identify the main sensory and motor areas of the cerebrum
- outline the position and functions of the thalamus and hypothalamus
- describe the position and functions of the midbrain, pons, medulla oblongata and reticular activating system
- describe the structure and functions of the cerebellum.

The brain is a large organ weighing around 1.4 kg that lies within the cranial cavity. Its parts are (Fig. 7.17):

- cerebrum
- thalamus, hypothalamus } the diencephalon
- midbrain, pons, medulla oblongata } the brain stem
- cerebellum **7.6, 7.7**

Blood supply and venous drainage

The *circulus arteriosus* and its contributing arteries (see Fig. 5.31, p. 105) play a vital role in maintaining a constant supply of oxygen and glucose to the brain when the head is moved and also if a contributing artery is narrowed. The brain receives about 15% of the cardiac output, approximately 750 mL of blood per minute. Autoregulation keeps blood flow to the brain constant by adjusting the diameter of the arterioles across a wide range of arterial blood pressure (about 65–140 mmHg) with changes occurring only outside these limits.

Venous blood from the brain drains into the *dural venous sinuses* and then downwards into the *internal jugular veins* (see Figs 5.34 and 5.35, p. 106).

Cerebrum

This is the largest part of the brain and it occupies the anterior and middle cranial fossae (see Fig. 16.11, p. 398). It is divided by a deep cleft, the *longitudinal cerebral fissure*, into *right* and *left cerebral hemispheres*, each

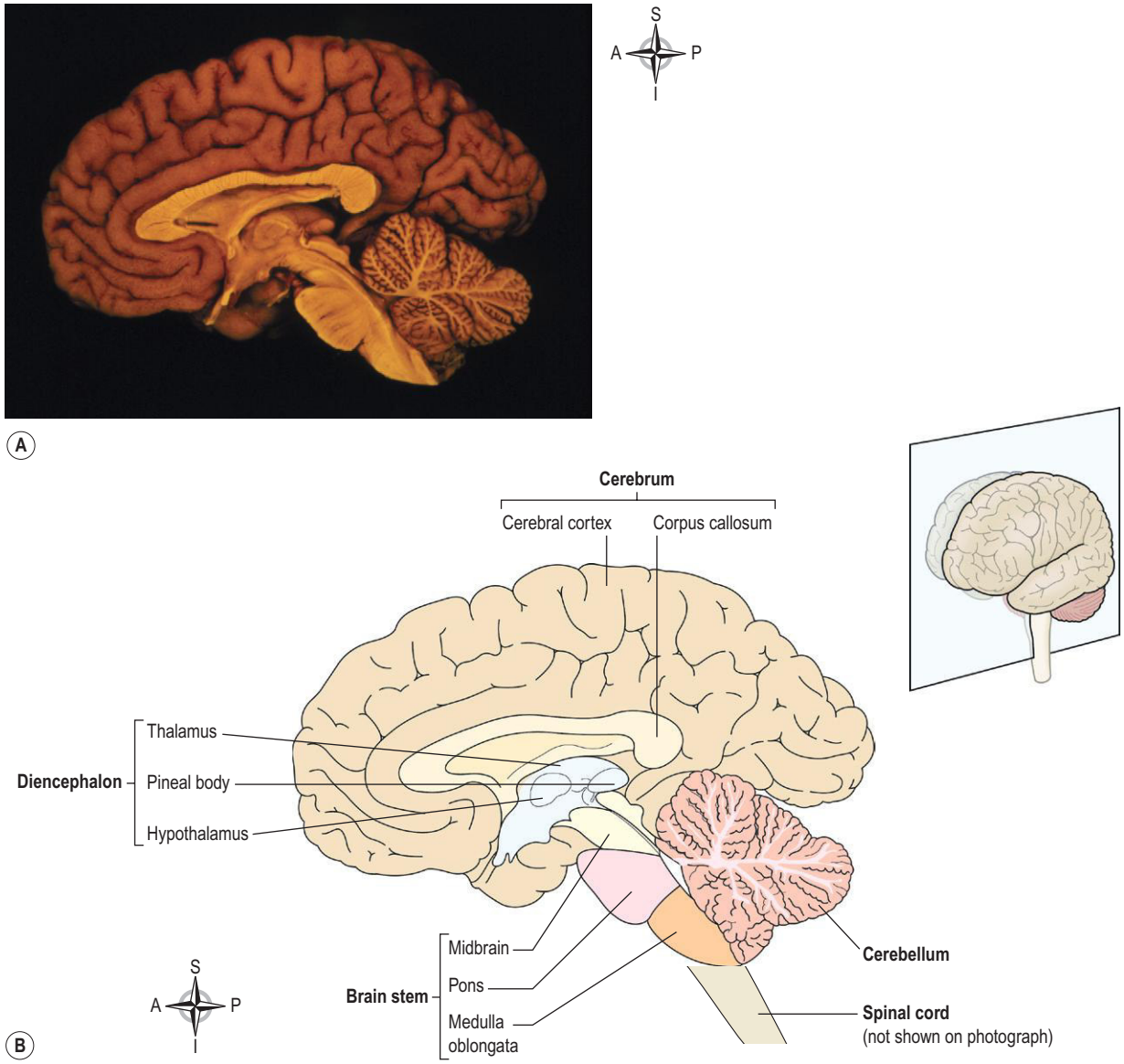

Figure 7.17 A midsaggital section of the brain showing the main parts.

containing one of the lateral ventricles. Deep within the brain, the hemispheres are connected by a mass of white matter (nerve fibres) called the *corpus callosum*. The falx cerebri is formed by the dura mater (see Fig. 7.14). It separates the two cerebral hemispheres and penetrates to the depth of the corpus callosum. The superficial part of the cerebrum is composed of nerve cell bodies (grey matter), forming the *cerebral cortex*, and the deeper layers consist of nerve fibres (axons, white matter).

The cerebral cortex shows many infoldings or furrows of varying depth. The exposed areas of the folds are the *gyri* (convolutions) and these are separated by *sulci* (fissures). These convolutions greatly increase the surface area of the cerebrum.

For descriptive purposes each hemisphere of the cerebrum is divided into *lobes* which take the names of the bones of the cranium under which they lie:

- frontal
- parietal
- temporal
- occipital.

The boundaries of the lobes are marked by deep sulci. These are the *central*, *lateral* and *parieto-occipital sulci* (Fig. 7.18).

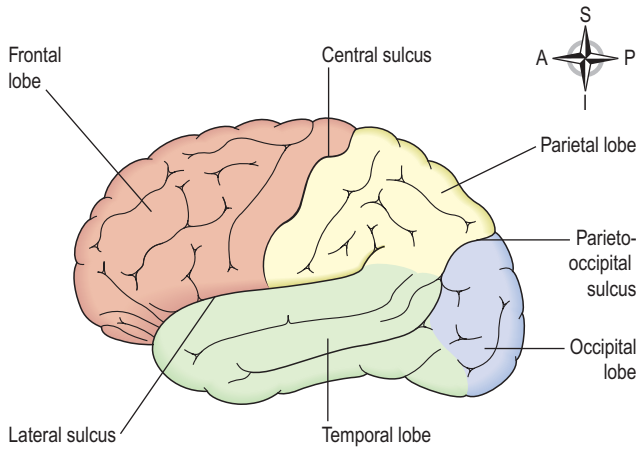

Figure 7.18 The lobes and principal sulci of the cerebrum. Viewed from the left side.

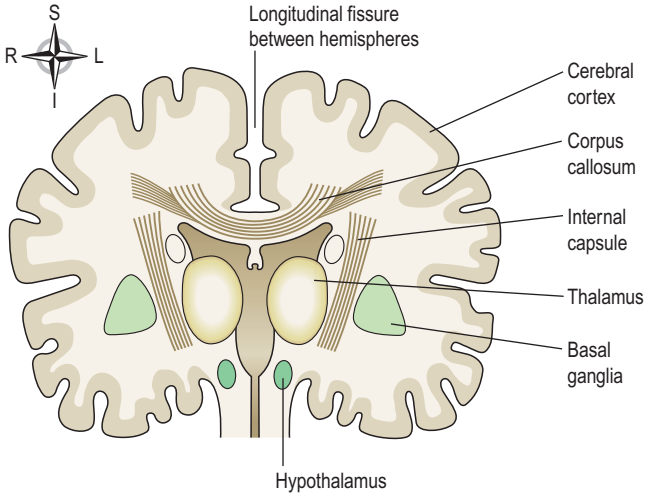

Figure 7.19 A frontal section of the cerebrum. Important tracts are shown in dark brown.

Cerebral tracts and basal ganglia (Fig. 7.19)

The surface of the cerebral cortex is composed of grey matter (nerve cell bodies). Within the cerebrum the lobes are connected by masses of nerve fibres, or *tracts*, which make up the white matter of the brain. The afferent and efferent fibres linking the different parts of the brain and spinal cord are as follows.

- *Association* (*arcuate*) *tracts* are most numerous and connect different parts of a cerebral hemisphere by extending from one gyrus to another, some of which are adjacent and some distant.
- *Commissural tracts* connect corresponding areas of the two cerebral hemispheres; the largest and most important commissure is the *corpus callosum*.
- *Projection tracts* connect the cerebral cortex with grey matter of lower parts of the brain and with the spinal cord, e.g. the internal capsule.

The *internal capsule* (Fig. 7.19) is an important projection tract that lies deep within the brain between the basal ganglia and the thalamus. Many nerve impulses passing to and from the cerebral cortex are carried by fibres that form the internal capsule. Motor fibres within the internal capsule form the *pyramidal tracts* (corticospinal tracts) that cross over (decussate) at the medulla oblongata and are the main pathway to skeletal muscles. Those motor fibres that do not pass through the internal capsule form the *extrapyramidal tracts* and have connections with many parts of the brain including the basal ganglia, thalamus and cerebellum.

Basal ganglia

The basal ganglia are groups of cell bodies that lie deep within the brain and form part of the extrapyramidal tracts. They act as relay stations with connections to many parts of the brain including motor areas of the cerebral cortex and thalamus. Their functions include initiation and fine control of complex movement and learned coordinated activities, such as posture and walking. If control is inadequate or absent, movements are jerky, clumsy and uncoordinated.

Functions of the cerebral cortex

There are three main types of activity associated with the cerebral cortex:

- higher order functions, i.e. the mental activities involved in memory, sense of responsibility, thinking, reasoning, moral decision making and learning
- sensory perception, including the perception of pain, temperature, touch, sight, hearing, taste and smell
- initiation and control of skeletal muscle contraction and therefore voluntary movement.

Functional areas of the cerebral cortex (Fig. 7.20)

The main functional areas of the cerebral cortex have been identified but it is unlikely that any area is associated exclusively with only one function. Except where specially mentioned, the different areas are active in both hemispheres; however, there is some variation between individuals. There are different types of functional area:

- motor, which direct skeletal (voluntary) muscle movements
- sensory, which receive and decode sensory impulses enabling sensory perception
- association, which are concerned with integration and processing of complex mental functions such as intelligence, memory, reasoning, judgement and emotions.

In general, areas of the cortex lying anterior to the central sulcus are associated with motor functions,

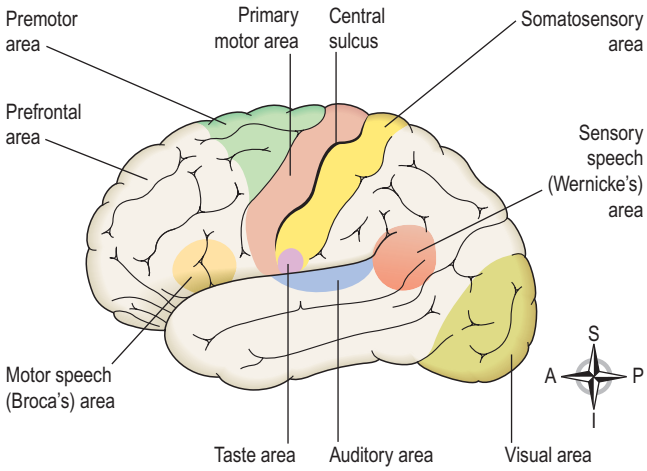

Figure 7.20 The cerebrum showing the main functional areas. Viewed from the left side.

and those lying posterior to it are associated with sensory functions.

Motor areas of the cerebral cortex

The primary motor area. This lies in the frontal lobe immediately anterior to the central sulcus. The cell bodies are pyramid shaped (Betz's cells) and they control skeletal muscle activity. Two neurones involved in the pathway to skeletal muscle. The first, the *upper motor neurone,* descends from the motor cortex through the internal capsule to the medulla oblongata. Here it crosses to the opposite side and descends in the spinal cord. At the appropriate level in the spinal cord it synapses with a second neurone (the *lower motor neurone*), which leaves the spinal cord and travels to the target muscle. It terminates at the motor end plate of a muscle fibre (Fig. 7.21). This means that the motor area of the right hemisphere of the cerebrum controls voluntary muscle movement on the left side of the body and vice versa. Damage to either of these neurones may result in paralysis.

In the motor area of the cerebrum the body is represented upside down, i.e. the uppermost cells control the feet and those in the lowest part control the head, neck, face and fingers (Fig. 7.22A). The sizes of the areas of cortex representing different parts of the body are proportional to the complexity of movement of the body part, not to its size. Figure 7.22A shows that – in comparison with the trunk – the hand, foot, tongue and lips are represented by large cortical areas reflecting the greater degree of motor control associated with these areas.

Motor speech (Broca's) area. This is situated in the frontal lobe just above the lateral sulcus and controls the muscle movements needed for speech. It is dominant in the left hemisphere in right-handed people and vice versa.

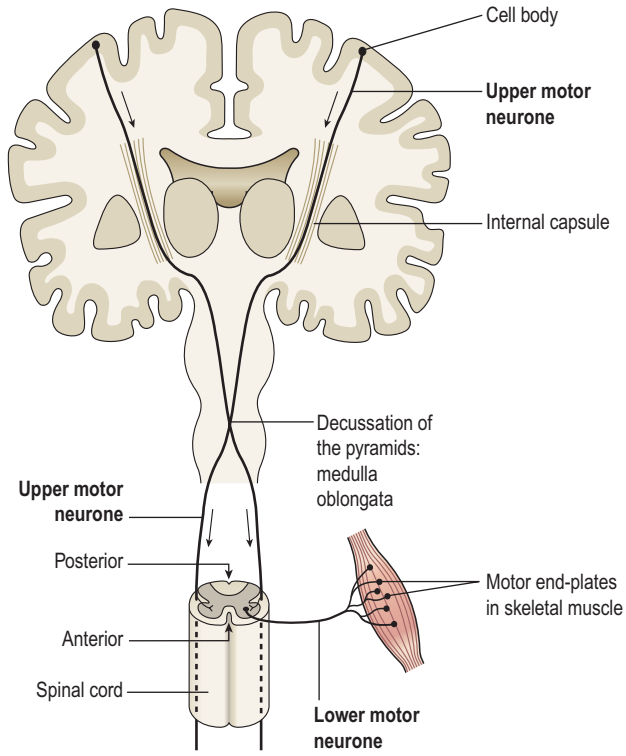

Figure 7.21 The motor nerve pathways: upper and lower motor neurones.

Sensory areas of the cerebral cortex

The somatosensory area. This is the area immediately behind the central sulcus. Here sensations of pain, temperature, pressure and touch, awareness of muscular movement and the position of joints (proprioception) are perceived. The somatosensory area of the right hemisphere receives impulses from the left side of the body and vice versa. The size of the cortical areas representing different parts of the body (Fig. 7.22B) is proportional to the extent of sensory innervation, e.g. the large area for the face is consistent with the extensive sensory nerve supply by the three branches of the trigeminal nerves (5th cranial nerves).

The auditory (hearing) area. This lies immediately below the lateral sulcus within the temporal lobe. The nerve cells receive and interpret impulses transmitted from the inner ear by the cochlear (auditory) part of the vestibulocochlear nerves (8th cranial nerves).

The olfactory (smell) area. This lies deep within the temporal lobe where impulses from the nose, transmitted via the olfactory nerves (1st cranial nerves), are received and interpreted.

The taste area. This lies just above the lateral sulcus in the deep layers of the somatosensory area. Here, impulses from sensory receptors in taste buds are received and perceived as taste.

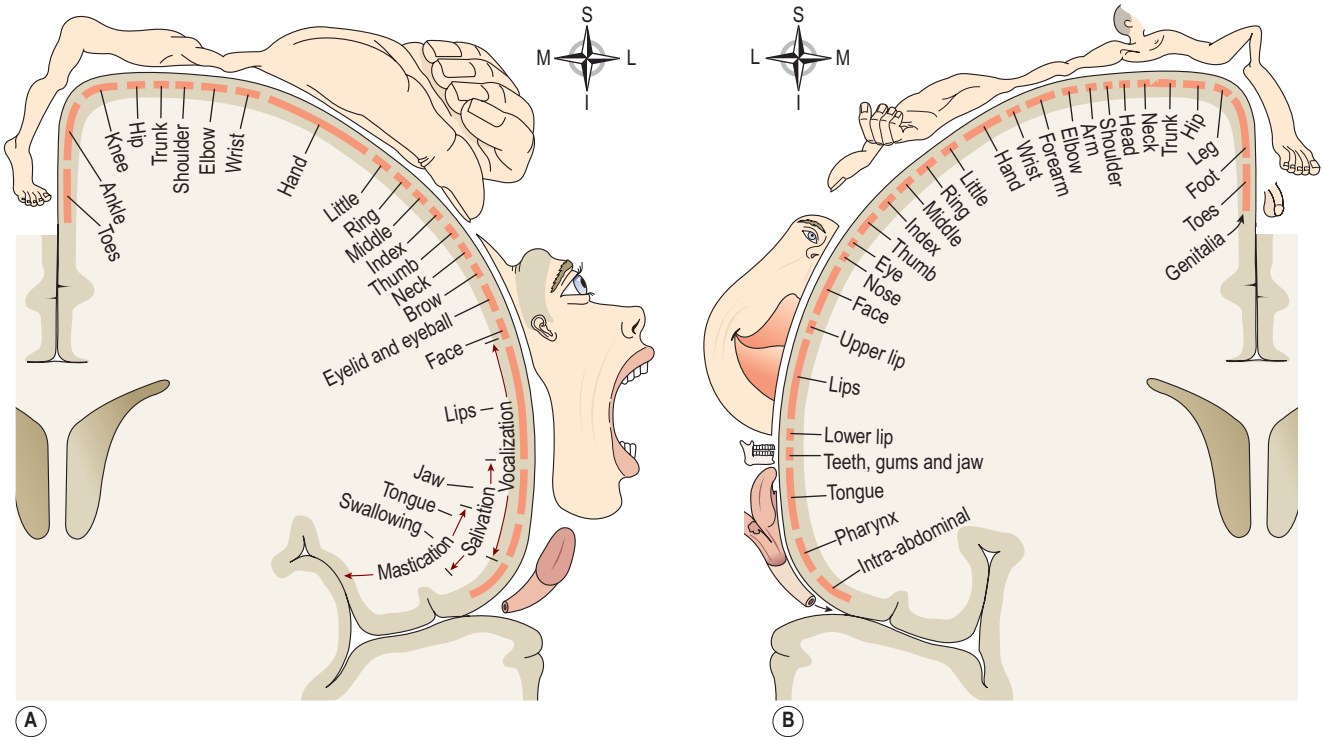

Figure 7.22 Functional areas of the cerebral cortex. A. The motor homunculus showing how the body is represented in the motor area of the cerebrum. **B.** The sensory homunculus showing how the body is represented in the sensory area of the cerebrum

The visual area. This lies behind the parieto-occipital sulcus and includes the greater part of the occipital lobe. The optic nerves (2nd cranial nerves) pass from the eye to this area, which receives and interprets the impulses as visual impressions.

Association areas

These are connected to each other and other areas of the cerebral cortex by association tracts and some are outlined below. They receive, coordinate and interpret impulses from the sensory and motor cortices permitting higher cognitive abilities and, although Figure 7.23 depicts some of the areas involved, their functions are much more complex.

The premotor area. This lies in the frontal lobe immediately anterior to the motor area. The neurones here coordinate movement initiated by the primary motor cortex, ensuring that learned patterns of movement can be repeated. For example, in tying a shoelace or writing, many muscles contract but the movements must be coordinated and carried out in a particular sequence. Such a pattern of movement, when established, is described as *manual dexterity*.

The prefrontal area. This extends anteriorly from the premotor area to include the remainder of the frontal lobe. It is a large area and is more highly developed in humans than in other animals. Intellectual functions controlled here include perception and comprehension of the passage of time, the ability to anticipate consequences of events and the normal management of emotions.

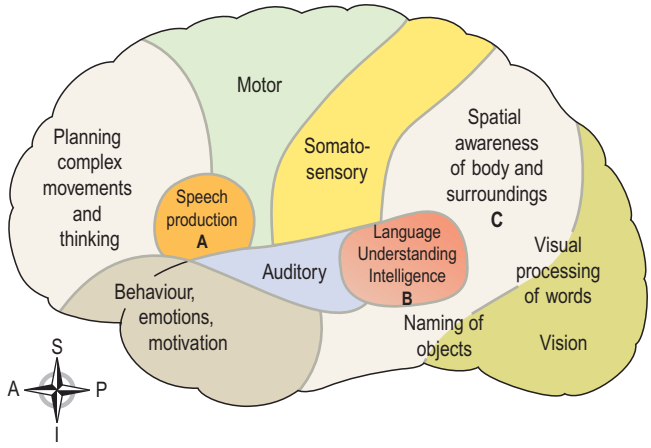

Figure 7.23 Areas of the cerebral cortex involved in higher mental functions. A. Motor speech (Broca's) area. **B.** Sensory speech (Wernicke's) area. **C.** Parieto-occipital area.

Sensory speech (Wernicke's) area. This is situated in the temporal lobe adjacent to the parieto-occipitotemporal area. It is here that the spoken word is perceived, and comprehension and intelligence are based. Understanding language is central to higher mental functions as they are language based. This area is dominant in the left hemisphere in right-handed people and vice versa.

The parieto-occipitotemporal area This lies behind the somatosensory area and includes most of the parietal lobe. Its functions are thought to include spatial awareness, interpreting written language and the ability to name objects (Fig. 7.23). It has been suggested that objects can be recognised by touch alone because of the knowledge from past experience (memory) retained in this area.

Diencephalon (see Fig. 7.17)

This connects the cerebrum and the midbrain. It consists of several structures situated around the third ventricle, the main ones being the thalamus and hypothalamus, which are considered here. The pineal gland (p. 228) and the optic chiasma (p. 199) are situated there.

Thalamus

This consists of two masses of grey and white matter situated within the cerebral hemispheres just below the corpus callosum, one on each side of the third ventricle (Fig. 7.19). Sensory receptors in the skin and viscera send information about touch, pain and temperature, and input from the special sense organs travels to the thalamus where there is recognition, although only in a basic form, as refined perception also involves other parts of the brain. It is thought to be involved in the processing of some emotions and complex reflexes. The thalamus relays and redistributes impulses from most parts of the brain to the cerebral cortex.

Hypothalamus

The hypothalamus is a small but important structure which weighs around 7 g and consists of a number of nuclei. It is situated below and in front of the thalamus, immediately above the *pituitary gland*. The hypothalamus is linked to the posterior lobe of the pituitary gland by nerve fibres and to the anterior lobe by a complex system of blood vessels. Through these connections, the hypothalamus controls the output of hormones from both lobes of the pituitary gland (see p. 217).

Other functions of the hypothalamus include control of:

- the autonomic nervous system (p. 173)
- appetite and satiety
- thirst and water balance
- body temperature (p. 365)
- emotional reactions, e.g. pleasure, fear, rage
- sexual behaviour and child rearing
- sleeping and waking cycles.

Brain stem (Fig. 7.17)

Midbrain

The midbrain is the area of the brain situated around the cerebral aqueduct (see Fig. 7.15) between the cerebrum above and the *pons* below. It consists of nuclei and nerve fibres (tracts), which connect the cerebrum with lower parts of the brain and with the spinal cord. The nuclei act as relay stations for the ascending and descending nerve fibres and have important roles in auditory and visual reflexes.

Pons

The pons is situated in front of the cerebellum, below the midbrain and above the medulla oblongata. It consists mainly of nerve fibres (white matter) that form a bridge between the two hemispheres of the cerebellum, and of fibres passing between the higher levels of the brain and the spinal cord. There are nuclei within the pons that act as relay stations and some of these are associated with the cranial nerves. Others form the *pneumotaxic* and *apnoustic centres* that operate in conjunction with the respiratory centre in the medulla oblongata to control respiration (Ch. 10).

The anatomical structure of the pons differs from that of the cerebrum in that the cell bodies (grey matter) lie deeply and the nerve fibres are on the surface.

Medulla oblongata

The medulla oblongata, or simply the medulla, is the most interior region of the brain stem (see Fig. 7.24). Extending from the pons above, it is continuous with the spinal cord below (see Fig. 7.24). It is about 2.5 cm long and lies just within the cranium above the foramen magnum. Its anterior and posterior surfaces are marked by central fissures. The outer aspect is composed of white matter, which passes between the brain and the spinal cord, and grey matter, which lies centrally. Some cells constitute relay stations for sensory nerves passing from the spinal cord to the cerebrum.

The *vital centres*, consisting of groups of cell bodies (nuclei) associated with autonomic reflex activity, lie in its deeper structure. These are the:

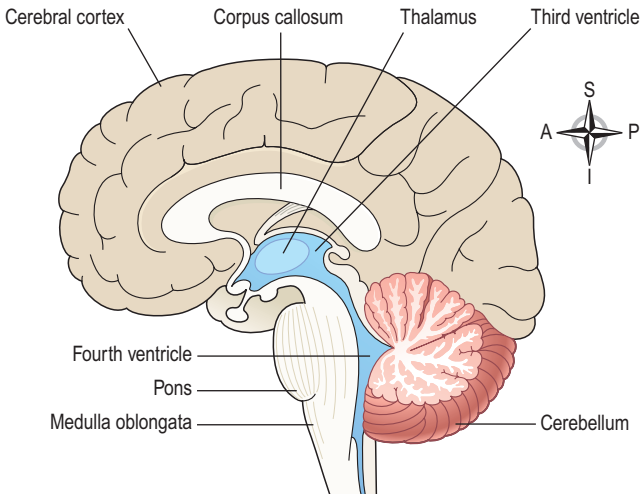

Figure 7.24 The cerebellum and associated structures.

- cardiovascular centre
- respiratory centre
- reflex centres of vomiting, coughing, sneezing and swallowing.

The medulla oblongata has several special features.

Decussation (crossing) of the pyramids. In the medulla, motor nerves descending from the motor area in the cerebrum to the spinal cord in the pyramidal (corticospinal) tracts cross from one side to the other. This means that the left hemisphere of the cerebrum controls the right half of the body, and vice versa. These tracts are the main pathway to skeletal (voluntary) muscles.

Sensory decussation. Some of the sensory nerves ascending to the cerebrum from the spinal cord cross from one side to the other in the medulla. Others decussate lower down in the spinal cord.

The cardiovascular centre (CVC). This area controls the rate and force of cardiac contraction (p. 97). It also controls blood pressure (p. 97). Within the CVC, other groups of nerve cells forming the *vasomotor centre* (p. 84) control the diameter of the blood vessels, especially the small arteries and arterioles. The vasomotor centre is stimulated by the arterial baroreceptors, body temperature and emotions such as sexual excitement and anger. Pain usually causes vasoconstriction although severe pain may cause vasodilation, a fall in blood pressure and fainting.

The respiratory centre. This area controls the rate and depth of respiration. From here, nerve impulses pass to the phrenic and intercostal nerves which stimulate contraction of the diaphragm and intercostal muscles, thus initiating inspiration. It functions in close association with the pnuemotaxic and apneustic centres in the pons (see p. 260).

Reflex centres. Irritants present in the stomach or respiratory tract stimulate the medulla oblongata, activating the reflex centres. Vomiting, coughing and sneezing are protective reflexes that attempt to expel irritants.

Reticular formation

The reticular formation is a collection of neurones in the core of the brain stem, surrounded by neural pathways that conduct ascending and descending nerve impulses between the brain and the spinal cord. It has a vast number of synaptic links with other parts of the brain and is therefore constantly receiving 'information' being transmitted in ascending and descending tracts.

Functions

The reticular formation is involved in:

- coordination of skeletal muscle activity associated with voluntary motor movement and the maintenance of balance
- coordination of activity controlled by the autonomic nervous system, e.g. cardiovascular, respiratory and gastrointestinal activity (p. 173)
- selective awareness that functions through the *reticular activating system* (RAS), which selectively blocks or passes sensory information to the cerebral cortex, e.g. the slight sound made by a sick child moving in bed may arouse the mother but the noise of regularly passing trains does not disturb her.

Cerebellum

The cerebellum (Fig. 7.24) is situated behind the pons and immediately below the posterior portion of the cerebrum occupying the posterior cranial fossa. It is ovoid in shape and has two hemispheres, separated by a narrow median strip called the *vermis*. Grey matter forms the surface of the cerebellum, and the white matter lies deeply.

Functions

The cerebellum is concerned with the coordination of voluntary muscular movement, posture and balance. Cerebellar activity is not under voluntary control. The cerebellum controls and coordinates the movements of various groups of muscles ensuring smooth, even, precise actions. It coordinates activities associated with the *maintenance of posture, balance* and *equilibrium*. The sensory input for these functions is derived from the muscles and joints, the eyes and the ears. *Proprioceptor impulses* from the muscles and joints indicate their position in relation to the body as a whole; impulses from the eyes and the semicircular canals in the ears provide information about the position of the head in space. The cerebellum integrates this information to regulate skeletal muscle activity so that balance and posture are maintained.

The cerebellum may also have a role in learning and language processing.

Damage to the cerebellum results in clumsy uncoordinated muscular movement, staggering gait and inability to carry out smooth, steady, precise movements.

Spinal cord

Learning outcomes

After studying this section, you should be able to:

- describe the gross structure of the spinal cord
- state the functions of the sensory (afferent) and motor (efferent) nerve tracts in the spinal cord
- explain the events of a simple reflex arc.

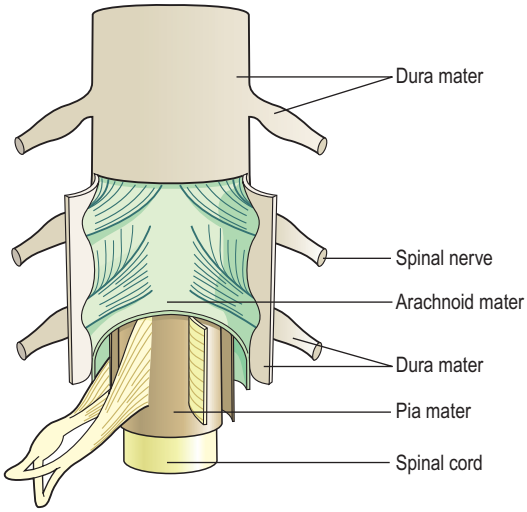

Figure 7.25 The meninges covering the spinal cord. Each cut away to show the underlying layers.

The spinal cord is the elongated, almost cylindrical part of the central nervous system, which is suspended in the vertebral canal surrounded by the meninges and cerebrospinal fluid (Fig. 7.25). The meninges are described on page 152. The spinal cord is continuous above with the medulla oblongata and extends from the upper border of the atlas (first cervical vertebra) to the lower border of the 1st lumbar vertebra (Fig. 7.26). It is approximately 45 cm long in adult males, and is about the thickness of the little finger. A specimen of cerebrospinal fluid can be taken using a procedure called *lumbar puncture* (p. 153).

Except for the cranial nerves, the spinal cord is the nervous tissue link between the brain and the rest of the body (Fig. 7.27). Nerves conveying impulses from the brain to the various organs and tissues descend through the spinal cord. At the appropriate level they leave the cord and pass to the structure they supply. Similarly, sensory nerves from organs and tissues enter and pass upwards in the spinal cord to the brain.

Some activities of the spinal cord are independent of the brain and are controlled at the level of the spinal cord by *spinal reflexes*. To facilitate these, there are extensive neurone connections between sensory and motor neurones at the same or different levels in the cord.

The spinal cord is incompletely divided into two equal parts, anteriorly by a short, shallow *median fissure* and posteriorly by a deep narrow septum, the *posterior median septum*.

A cross-section of the spinal cord shows that it is composed of grey matter in the centre surrounded by white matter supported by neuroglia. Figure 7.28 shows the parts of the spinal cord and the nerve roots on one side. The other side is the same. **7.8**

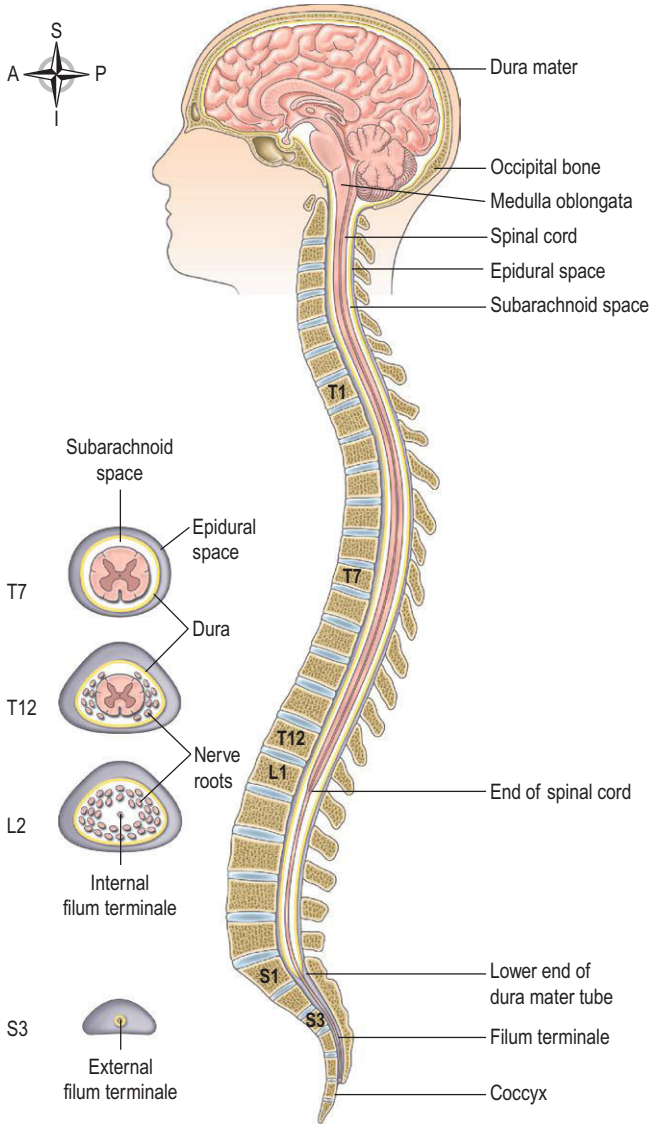

Figure 7.26 Sections of the vertebral canal showing the epidural space.

Grey matter

The arrangement of grey matter in the spinal cord resembles the shape of the letter H, having *two posterior*, *two anterior* and *two lateral columns*. The area of grey matter lying transversely is the *transverse commissure* and it is pierced by the central canal, an extension from the fourth ventricle, containing cerebrospinal fluid. The nerve cell bodies may belong to:

- *sensory neurones*, which receive impulses from the periphery of the body
- *lower motor neurones*, which transmit impulses to the skeletal muscles
- *connector neurones*, also known as interneurones linking sensory and motor neurones, at the same or different levels, which form spinal reflex arcs.

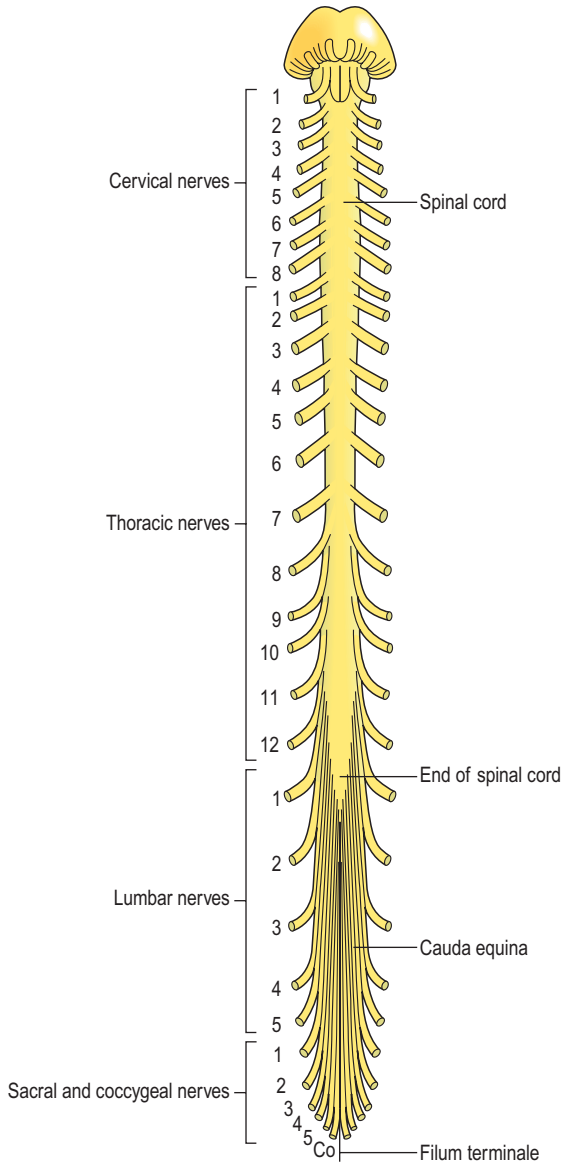

Figure 7.27 The spinal cord and spinal nerves.

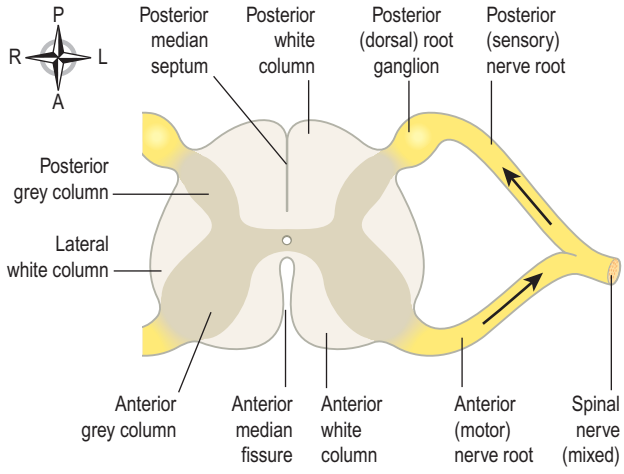

Figure 7.28 A transverse section of the spinal cord showing nerve roots on one side.

At each point where nerve impulses are transmitted from one neurone to another, there is a synapse (p. 147).

Posterior columns of grey matter

These are composed of cell bodies that are stimulated by sensory impulses from the periphery of the body. The nerve fibres of these cells contribute to the white matter of the cord and transmit the sensory impulses upwards to the brain.

Anterior columns of grey matter

These are composed of the cell bodies of the lower motor neurones that are stimulated by the upper motor neurones or the connector neurones linking the anterior and posterior columns to form reflex arcs.

The *posterior root* (*spinal*) *ganglia* are formed by the cell bodies of the sensory nerves.

White matter

The white matter of the spinal cord is arranged in three *columns* or *tracts*; anterior, posterior and lateral. These tracts are formed by sensory nerve fibres ascending to the brain, motor nerve fibres descending from the brain and fibres of connector neurones.

Tracts are often named according to their points of origin and destination, e.g. spinothalamic, corticospinal.

Sensory nerve tracts in the spinal cord

Neurones that transmit impulses towards the brain are called sensory (afferent, ascending). There are two main sources of sensation transmitted to the brain via the spinal cord.

1. *The skin*. Sensory receptors (nerve endings) in the skin are stimulated by pain, heat, cold and touch, including pressure (see Ch. 14). The nerve impulses generated are conducted by three neurones to the sensory area in the *opposite hemisphere of the cerebrum* where the sensation and its location are perceived (Fig. 7.29). Crossing to the other side, or decussation, occurs either at the level of entry into the cord or in the medulla.
2. *The tendons, muscles and joints*. Sensory receptors are specialised nerve endings in these structures, called *proprioceptors*, and they are stimulated by stretch. Together with impulses from the eyes and the ears, they are associated with the maintenance of balance and posture, and with perception of the position of the body in space. These nerve impulses have two destinations:
   - by a three-neurone system, the impulses reach the sensory area of the *opposite hemisphere of the cerebrum*
   - by a two-neurone system, the nerve impulses reach the *cerebellar hemisphere on the same side*.

Table 7.1 summarises the main sensory pathways.

Motor nerve tracts in the spinal cord

Neurones that transmit nerve impulses away from the brain are motor (efferent or descending) neurones. Stimulation of the motor neurones results in:

- contraction of skeletal (voluntary) muscle, or
- contraction of smooth (involuntary) muscle, cardiac muscle and the secretion by glands controlled by nerves of the autonomic nervous system (p. 173).

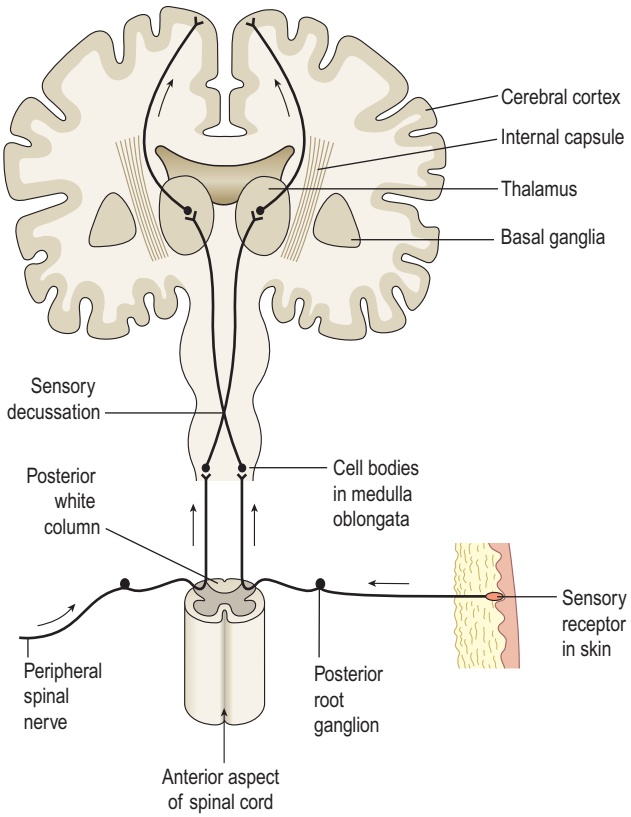

Figure 7.29 A sensory nerve pathway from the skin to the cerebrum.

Voluntary muscle movement

The contraction of muscles that move the joints is, in the main, under conscious (voluntary) control, which means that the stimulus to contract originates at the level of consciousness in the cerebrum. However, skeletal muscle activity is regulated by output from the midbrain, brain stem and cerebellum. This involuntary activity is associated with coordination of muscle activity, e.g. when very fine movement is required and in the maintenance of posture and balance.

Efferent nerve impulses are transmitted from the brain to other parts of the body via bundles of nerve fibres (tracts) in the spinal cord. The *motor pathways* from the brain to the muscles are made up of two neurones (see Fig. 7.21). These pathways, or tracts, are either:

- pyramidal (corticospinal), or
- extrapyramidal (p. 156).

The upper motor neurone. This has its cell body (Betz's cell) in the primary motor area of the cerebrum. The axons pass through the internal capsule, pons and medulla. In the spinal cord they form the lateral corticospinal tracts of white matter and the fibres synapse with the cell bodies of the lower motor neurones in the anterior columns of grey matter. The axons of the upper motor neurones make up the pyramidal tracts and decussate in the medulla oblongata, forming the pyramids.

The lower motor neurone. This has its cell body in the anterior horn of grey matter in the spinal cord. Its axon emerges from the spinal cord by the anterior root, joins with the incoming sensory fibres and forms the mixed spinal nerve that passes through the intervertebral foramen. Near its termination in skeletal muscle the axon branches into many tiny fibres, each of which is in close association with a sensitive area on the muscle fibre membrane known as a *motor end plate* (Figs 16.56 and 16.57, p. 422). The motor end plates of each nerve and the

Table 7.1 Sensory nerve impulses: origins, routes, destinations

Receptor	Route	Destination
Pain, touch, temperature	Neurone 1 – to spinal cord by posterior root Neurone 2 – decussation on entering spinal cord then in anterolateral spinothalamic tract to thalamus Neurone 3 –	to parietal lobe of cerebrum
Touch, proprioceptors	Neurone 1 – to medulla in posterior spinothalamic tract Neurone 2 – decussation in medulla, transmission to thalamus Neurone 3 –	to parietal lobe of cerebrum
Proprioceptors	Neurone 1 – to spinal cord Neurone 2 –	no decussation, to cerebellum in posterior spinocerebellar tract

muscle fibres they supply form a *motor unit*. The neurotransmitter that transmits the nerve impulse across the neuromuscular junction (synapse) to stimulate a skeletal muscle fibre is *acetylcholine*. Motor units contract as a whole and the strength of the muscle contraction depends on the number of motor units in action at any time.

The lower motor neurone is the *final common pathway* for the transmission of nerve impulses to skeletal muscles. The cell body of this neurone is influenced by a number of upper motor neurones originating from various sites in the brain and by some neurones which begin and end in the spinal cord. Some of these neurones stimulate the cell bodies of the lower motor neurone while others have an inhibiting effect. The outcome of these influences is smooth, coordinated muscle movement, some of which is voluntary and some involuntary.

Involuntary muscle movement

Upper motor neurones. These have their cell bodies in the brain at a level *below* the cerebrum, i.e. in the midbrain, brain stem, cerebellum or spinal cord. They influence muscle activity that maintains posture and balance, coordinates skeletal muscle movement and controls muscle tone.

Table 7.2 shows details of the area of origin of these neurones and the tracts which their axons form before reaching the cell body of the lower motor neurone in the spinal cord.

Spinal reflexes. These consist of three elements:

- sensory neurones
- connector neurones (or interneurones) in the spinal cord
- lower motor neurones.  **7.9**

In the simplest *reflex arc* there is only one of each type of the neurones above (Fig. 7.30). A *reflex action* is an involuntary and immediate motor response to a sensory stimulus. Many connector and motor neurones may be stimulated by afferent impulses from a small area of skin. For example, the pain impulses initiated by touching a very hot surface with the finger are transmitted to the spinal cord by sensory fibres in mixed nerves. These stimulate many connector and lower motor neurones in the spinal cord, which results in the contraction of many skeletal muscles of the hand, arm and shoulder, and the removal of the finger. Reflex action happens very quickly; in fact, the motor response may occur simultaneously with the perception of the pain in the cerebrum. Reflexes of this type are invariably protective but they can occasionally be inhibited. For example, if a precious plate is very hot when lifted every effort will be made to overcome the pain to prevent dropping it!

Stretch reflexes. Only two neurones are involved. The cell body of the lower motor neurone is stimulated directly by the sensory neurone, with no connector neurone in between (Fig. 7.30). The *knee jerk* is one example, but this type of reflex can be demonstrated at any point where a stretched tendon crosses a joint. By tapping the tendon just below the knee when it is bent, the sensory nerve endings in the tendon and in the thigh muscles are stretched. This initiates a nerve impulse that passes into the spinal cord to the cell body of the lower motor neurone in the anterior column of grey matter on the same side. As a result the thigh muscles suddenly contract and the foot kicks forward. This is used as a test of the integrity of the reflex arc. This type of reflex also has a protective function – it prevents excessive joint movement that may damage tendons, ligaments and muscles.

Autonomic reflexes. These include the pupillary light reflex when the pupil immediately constricts, in response to bright light, preventing retinal damage.

Table 7.2 Extrapyramidal upper motor neurones: origins and tracts

Origin	Name of tract	Site in spinal cord	Functions
Midbrain and pons	Rubrospinal tract decussates in brain stem	Lateral column	Control of skilled muscle movement
Reticular formation	Reticulospinal tract does not decussate	Lateral column	Coordination of muscle movement
Midbrain and pons	Tectospinal tract decussates in midbrain	Anterior colum	Maintenance of posture and balance
Midbrain and pons	Vestibulospinal tract, some fibres decussate in the cord	Anterior column	

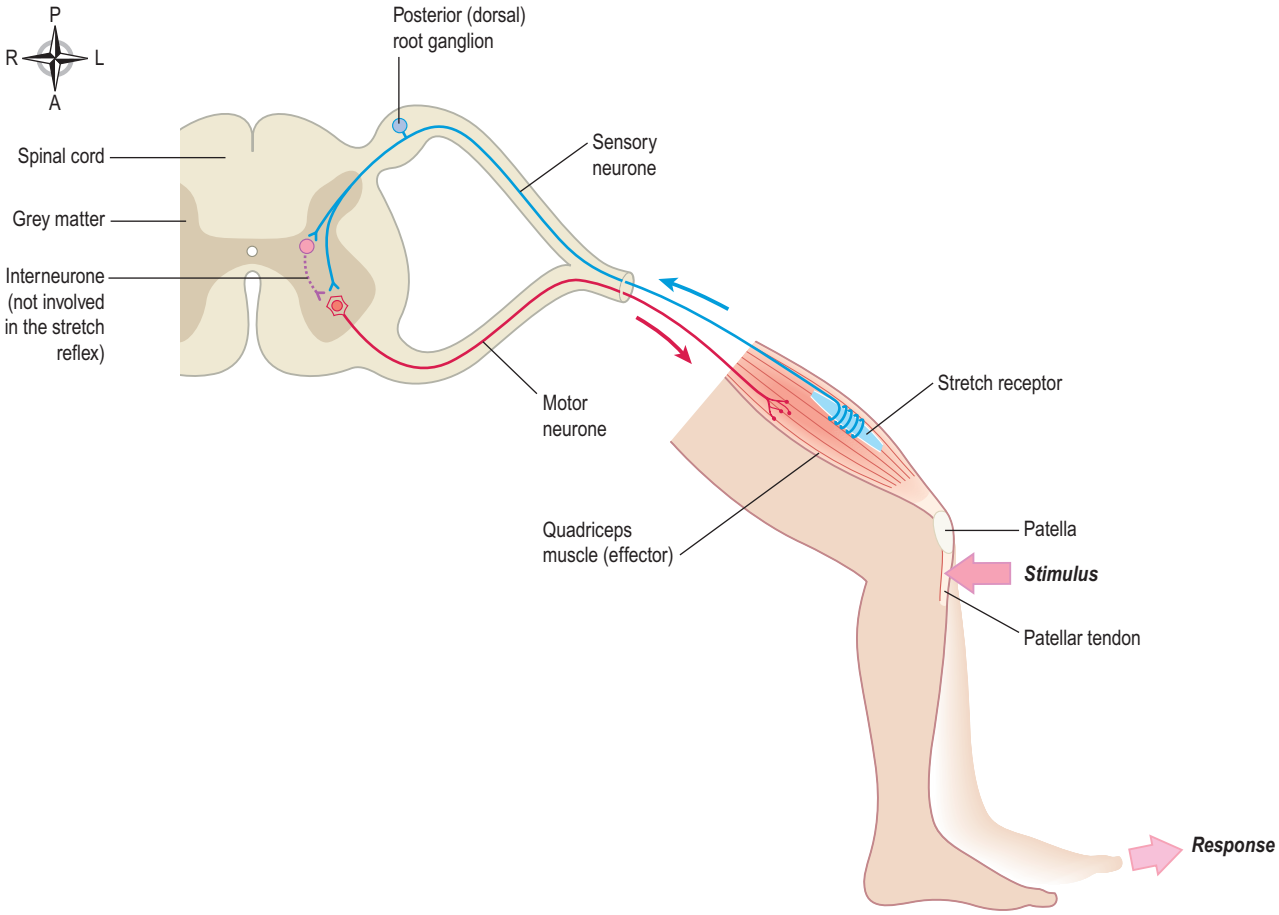

Figure 7.30 The knee jerk reflex. Left side.

Peripheral nervous system

Learning outcomes

After studying this section, you should be able to:

- outline the function of a nerve plexus
- list the spinal nerves entering each plexus and the main nerves emerging from it
- describe the areas innervated by the thoracic nerves
- outline the functions of the 12 cranial nerves
- compare and contrast the structures and neurotransmitters of the divisions of the autonomic nervous system
- compare and contrast the effects of stimulation of the divisions of the autonomic nervous system on body function.

This part of the nervous system consists of:

- 31 pairs of spinal nerves that originate from the spinal cord
- 12 pairs of cranial nerves, which originate from the brain
- the autonomic nervous system.

Most of the nerves of the peripheral nervous system are composed of sensory fibres that transmit afferent impulses from sensory organs to the brain, or motor nerve fibres that transmit efferent impulses from the brain to the effector organs, e.g. skeletal muscles, smooth muscle and glands.

Spinal nerves

Thirty-one pairs of spinal nerves leave the vertebral canal by passing through the intervertebral foramina formed by adjacent vertebrae. They are named and grouped according to the vertebrae with which they are associated (see Fig. 7.27):

- 8 cervical
- 12 thoracic
- 5 lumbar
- 5 sacral
- 1 coccygeal.

Although there are only seven cervical vertebrae, there are eight nerves because the first pair leaves the vertebral canal between the occipital bone and the atlas (first cervical vertebra) and the eighth pair leaves below the last

cervical vertebra. Thereafter the nerves are given the name and number of the vertebra immediately *above*.

The lumbar, sacral and coccygeal nerves leave the spinal cord near its termination, at the level of the 1st lumbar vertebra, and extend downwards inside the vertebral canal in the subarachnoid space, forming a sheaf of nerves which resembles a horse's tail, the *cauda equina* (see Fig. 7.27). These nerves leave the vertebral canal at the appropriate lumbar, sacral or coccygeal level, depending on their destination.

Nerve roots (Fig. 7.31)

The spinal nerves arise from both sides of the spinal cord and emerge through the intervertebral foramina (see Fig 16.26, p. 404). Each nerve is formed by the union of a *motor* (anterior) and a *sensory* (posterior) *nerve root* and is, therefore, a *mixed nerve*. Thoracic and upper lumbar (L1 and L2) spinal nerves have a contribution from the sympathetic part of the autonomic nervous system in the form of a *preganglionic fibre* (neurone).

Chapter 16 describes the bones and muscles mentioned in the following sections. Bones and joints are supplied by adjacent nerves.

The *anterior nerve root* consists of motor nerve fibres, which are the axons of the lower motor neurones from the anterior column of grey matter in the spinal cord and, in the thoracic and lumbar regions, *sympathetic nerve fibres*, which are the axons of cells in the lateral columns of grey matter.

The *posterior nerve root* consists of sensory nerve fibres. Just outside the spinal cord there is a *spinal ganglion* (posterior, or dorsal, root ganglion), consisting of a little cluster of cell bodies. Sensory nerve fibres pass through these ganglia before entering the spinal cord. The area of skin whose sensory receptors contribute to each nerve is called a *dermatome* (see Figs 7.36 and 7.39).

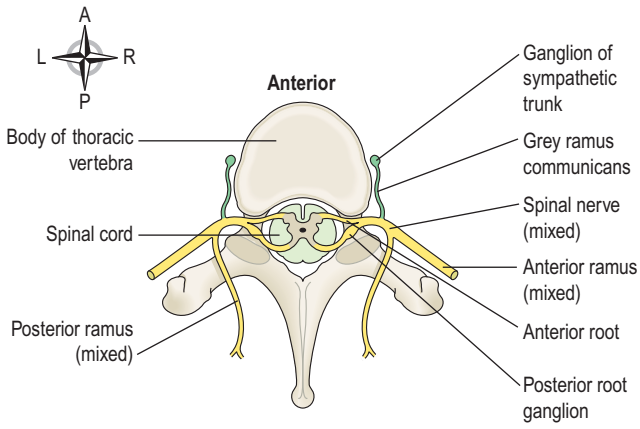

Figure 7.31 The relationship between sympathetic and mixed spinal nerves. Sympathetic nerves in green.

For a very short distance after leaving the spinal cord the nerve roots have a covering of *dura* and *arachnoid maters*. These terminate before the two roots join to form the mixed spinal nerve. The nerve roots have no covering of pia mater.

Branches

Immediately after emerging from the intervertebral foramen, spinal nerves divide into branches, or *rami*: a ramus communicans, a posterior ramus and an anterior ramus.

The *rami communicante* are part of preganglionic sympathetic neurones of the autonomic nervous system (p. 173).

The *posterior rami* pass backwards and divide into smaller medial and lateral branches to supply skin and muscles of relatively small areas of the posterior aspect of the head, neck and trunk.

The *anterior rami* supply the anterior and lateral aspects of the neck, trunk and the upper and lower limbs.

Plexuses

In the cervical, lumbar and sacral regions the anterior rami unite near their origins to form large masses of nerves, or *plexuses*, where nerve fibres are regrouped and rearranged before proceeding to supply skin, bones, muscles and joints of a particular area (Fig. 7.32). This means that these structures have a nerve supply from more than one spinal nerve and therefore damage to one spinal nerve does not cause loss of function of a region. Moreover, they lie deep within the body, often under large muscles, and are therefore well protected from injury.

In the thoracic region the anterior rami do not form plexuses.

There are five large plexuses of mixed nerves formed on each side of the vertebral column. They are the:

- cervical plexuses
- brachial plexuses
- lumbar plexuses
- sacral plexuses
- coccygeal plexuses.

Cervical plexus (Fig. 7.33)

This is formed by the anterior rami of the first four cervical nerves. It lies deep within the neck opposite the 1st, 2nd, 3rd and 4th cervical vertebrae under the protection of the sternocleidomastoid muscle.

The superficial branches supply the structures at the back and side of the head and the skin of the front of the neck to the level of the sternum.

The deep branches supply muscles of the neck, e.g. the sternocleidomastoid and the trapezius.

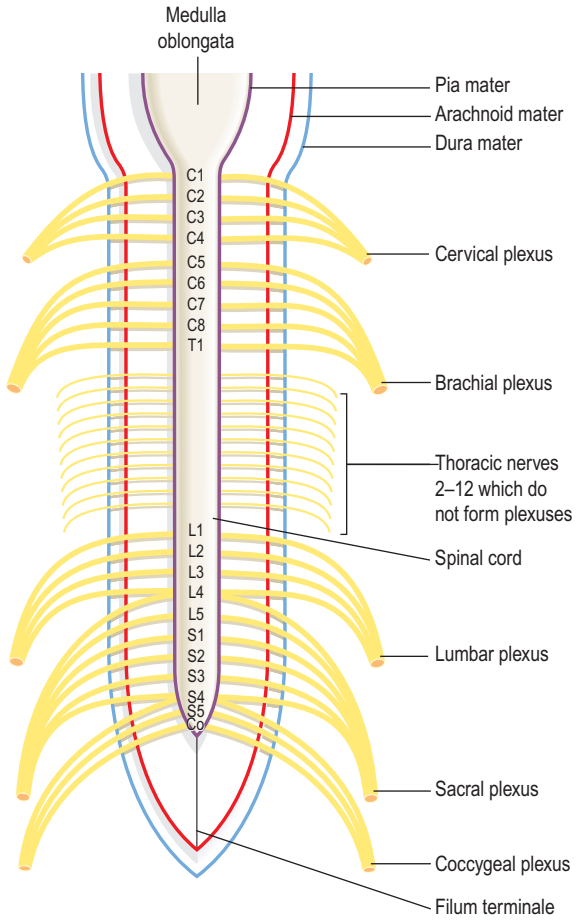

Figure 7.32 The meninges covering the spinal cord, spinal nerves and the plexuses they form.

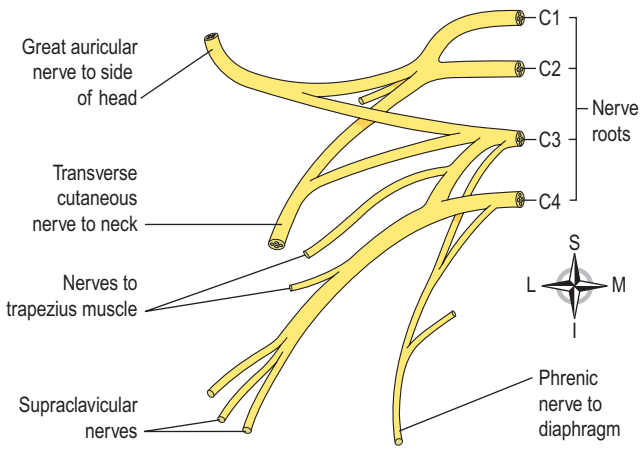

Figure 7.33 The cervical plexus. Anterior view.

The phrenic nerve originates from cervical nerve roots 3, 4 and 5 and passes downwards through the thoracic cavity in front of the root of the lung to supply the diaphragm, initiating inspiration. Disease or spinal cord injury at this level will result in death due to apnoea without assisted ventilation as spontaneous respiration is not possible.

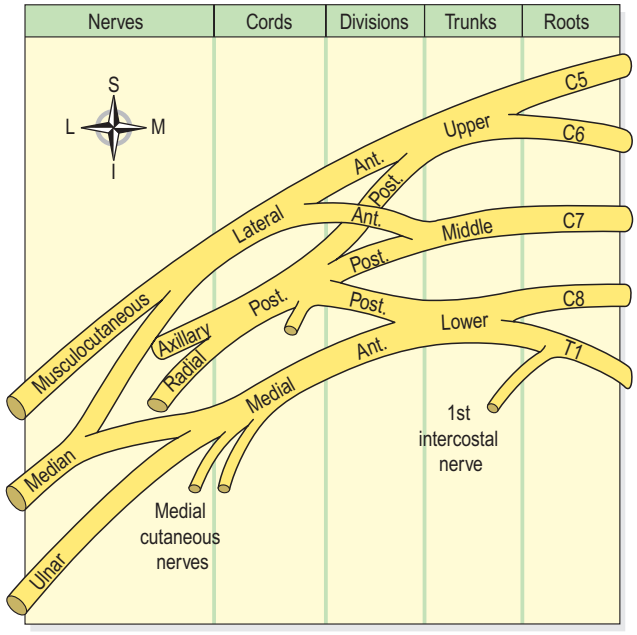

Figure 7.34 The brachial plexus. Anterior view. Ant = anterior, Post = posterior.

Brachial plexus

The anterior rami of the lower four cervical nerves and a large part of the 1st thoracic nerve form the brachial plexus. Figure 7.34 shows its formation and the nerves that emerge from it. The plexus is situated deeply within the neck and shoulder above and behind the subclavian vessels and in the axilla.

The branches of the brachial plexus supply the skin and muscles of the upper limbs and some of the chest muscles. Five large nerves and a number of smaller ones emerge from this plexus, each with a contribution from more than one nerve root, containing sensory, motor and autonomic fibres:

- axillary (circumflex) nerve: C5, 6
- radial nerve: C5, 6, 7, 8, T1
- musculocutaneous nerve: C5, 6, 7
- median nerve: C5, 6, 7, 8, T1
- ulnar nerve: C7, 8, T1
- medial cutaneous nerve: C8, T1.

The axillary (circumflex) nerve winds round the humerus at the level of the surgical neck. It then divides into minute branches to supply the deltoid muscle, shoulder joint and overlying skin.

The radial nerve is the largest branch of the brachial plexus. It supplies the triceps muscle behind the humerus, crosses in front of the elbow joint then winds round to the back of the forearm to supply extensor muscles of the wrist and finger joints. It continues into the back of the hand to supply the skin of the posterior aspect of the thumb, first two fingers and the lateral half of the third finger.

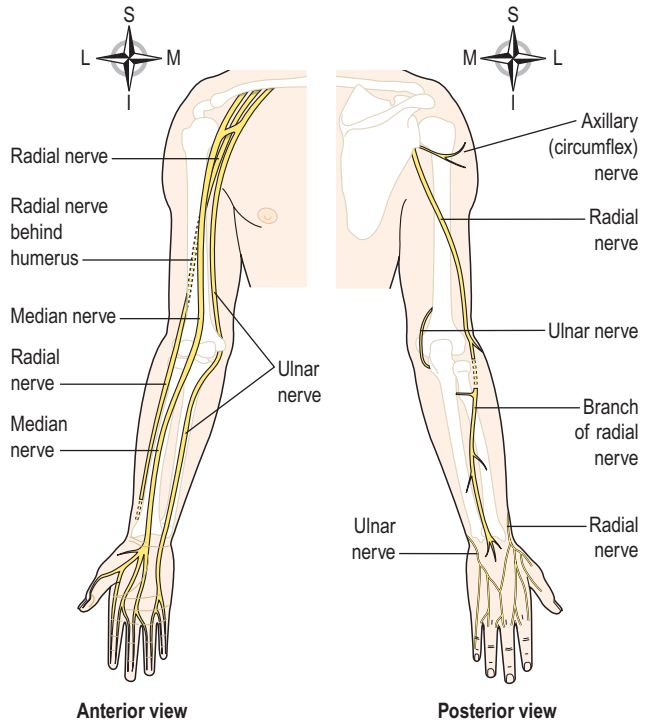

Figure 7.35 The main nerves of the arm.

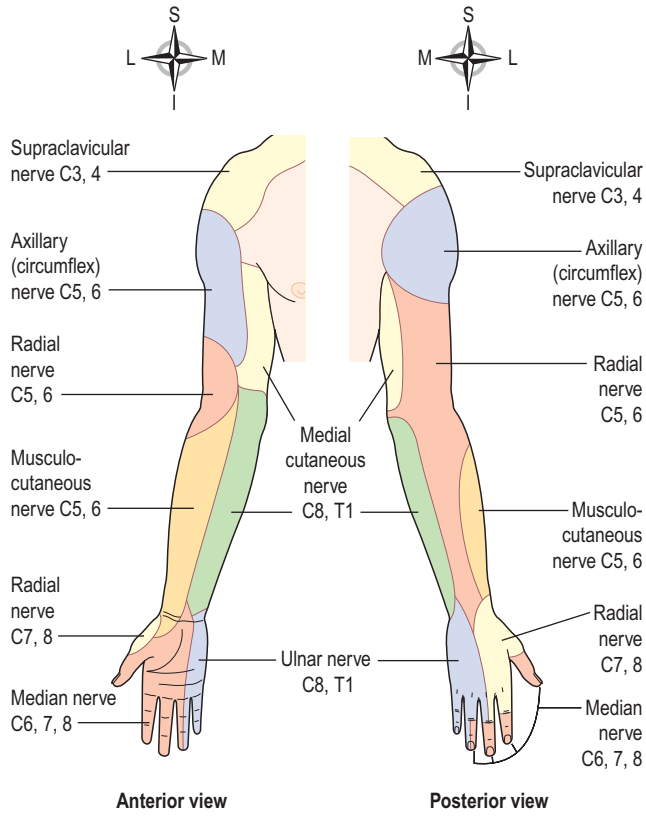

Figure 7.36 The distribution and origins of the cutaneous nerves of the arm. Colour distinguishes the dermatomes.

The musculocutaneous nerve passes downwards to the lateral aspect of the forearm. It supplies the muscles of the upper arm and the skin of the forearm.

The *median nerve* passes down the midline of the arm in close association with the brachial artery. It passes in front of the elbow joint then down to supply the muscles of the front of the forearm. It continues into the hand where it supplies small muscles and the skin of the front (palmar aspect) of the thumb, first two fingers and the lateral half of the third finger. It gives off no branches above the elbow.

The ulnar nerve descends through the upper arm lying medial to the brachial artery. It passes behind the medial epicondyle of the humerus to supply the muscles on the ulnar aspect of the forearm. It continues downwards to supply the muscles in the palm of the hand and the skin of the whole of the little finger and the medial half of the third finger. It gives off no branches above the elbow.

The main nerves of the arm are shown in Figure 7.35. The distribution and origins of the cutaneous sensory nerves of the arm, i.e. the dermatomes, are shown in Figure 7.36.

Lumbar plexus (Figs 7.37–7.39)

The lumbar plexus is formed by the anterior rami of the first three and part of the 4th lumbar nerves. The plexus is situated in front of the transverse processes of the lumbar vertebrae and behind the psoas muscle. The main branches and their nerve roots are:

- iliohypogastric nerve: L1
- ilioinguinal nerve: L1
- genitofemoral: L1, 2
- lateral cutaneous nerve of thigh: L2, 3
- femoral nerve: L2, 3, 4
- obturator nerve: L2, 3, 4
- lumbosacral trunk: L4, (5).

The iliohypogastric, ilioinguinal and *genitofemoral nerves* supply muscles and the skin in the area of the lower abdomen, upper and medial aspects of the thigh and the inguinal region.

The lateral cutaneous nerve of the thigh supplies the skin of the lateral aspect of the thigh including part of the anterior and posterior surfaces.

The femoral nerve is one of the larger branches. It passes behind the inguinal ligament to enter the thigh in close association with the femoral artery. It divides into cutaneous and muscular branches to supply the skin and the muscles of the front of the thigh. One branch, the *saphenous nerve*, supplies the medial aspect of the leg, ankle and foot.

The obturator nerve supplies the adductor muscles of the thigh and skin of the medial aspect of the thigh. It ends just above the level of the knee joint.

The lumbosacral trunk descends into the pelvis and makes a contribution to the sacral plexus.

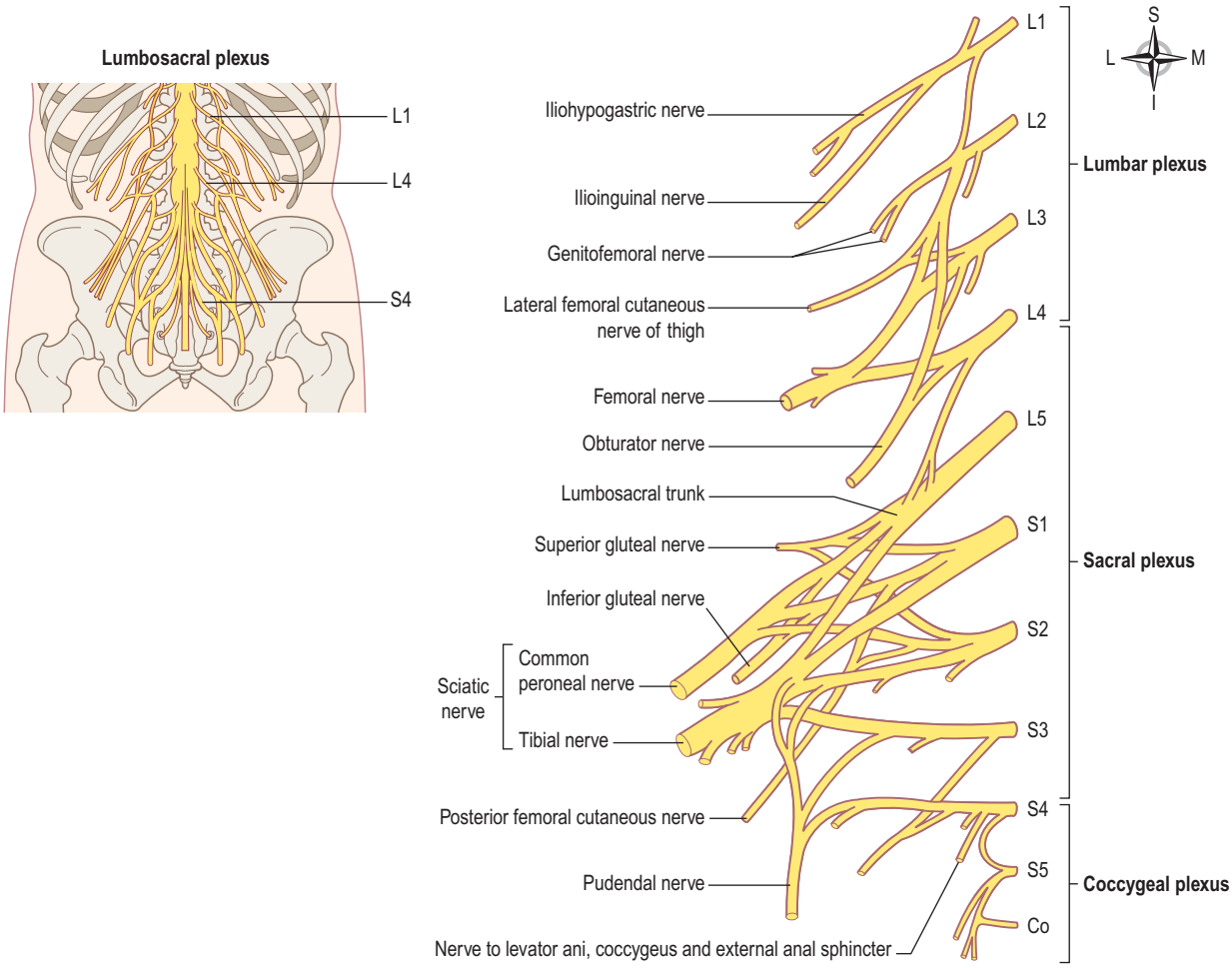

Figure 7.37 The lumbosacral and coccygeal plexuses.

Sacral plexus (Figs 7.37–7.39)

The sacral plexus is formed by the anterior rami of the lumbosacral trunk and the 1st, 2nd and 3rd sacral nerves. The lumbosacral trunk is formed by the 5th and part of the 4th lumbar nerves. It lies in the posterior wall of the pelvic cavity.

The sacral plexus divides into a number of branches, supplying the muscles and skin of the pelvic floor, muscles around the hip joint and the pelvic organs. In addition to these it provides the sciatic nerve, which contains fibres from L4 and 5 and S1–3.

The *sciatic nerve* is the largest nerve in the body. It is about 2 cm wide at its origin. It passes through the greater sciatic foramen into the buttock then descends through the posterior aspect of the thigh supplying the hamstring muscles. At the level of the middle of the femur it divides to form the *tibial* and the *common peroneal nerves*.

The tibial nerve descends through the popliteal fossa to the posterior aspect of the leg where it supplies muscles and skin. It passes under the medial malleolus to supply muscles and skin of the sole of the foot and toes. One of the main branches is the *sural nerve*, which supplies the tissues in the area of the heel, the lateral aspect of the ankle and a part of the dorsum of the foot.

The common peroneal nerve descends obliquely along the lateral aspect of the popliteal fossa, winds round the neck of the fibula into the front of the leg where it divides into the *deep peroneal* (anterior tibial) and the *superficial peroneal* (musculocutaneous) *nerves*. These nerves supply the skin and muscles of the anterior aspect of the leg and the dorsum of the foot and toes.

The pudendal nerve (S2, 3, 4) – the perineal branch supplies the external anal sphincter, the external urethral sphincter and adjacent skin. Figures 7.38 and 7.39 show the main nerves of the leg, the dermatomes and the origins of the main nerves.

Coccygeal plexus (Fig. 7.37)

The coccygeal plexus is a very small plexus formed by part of the 4th and 5th sacral and the coccygeal nerves. The nerves from this plexus supply the skin around the coccyx and anal area.

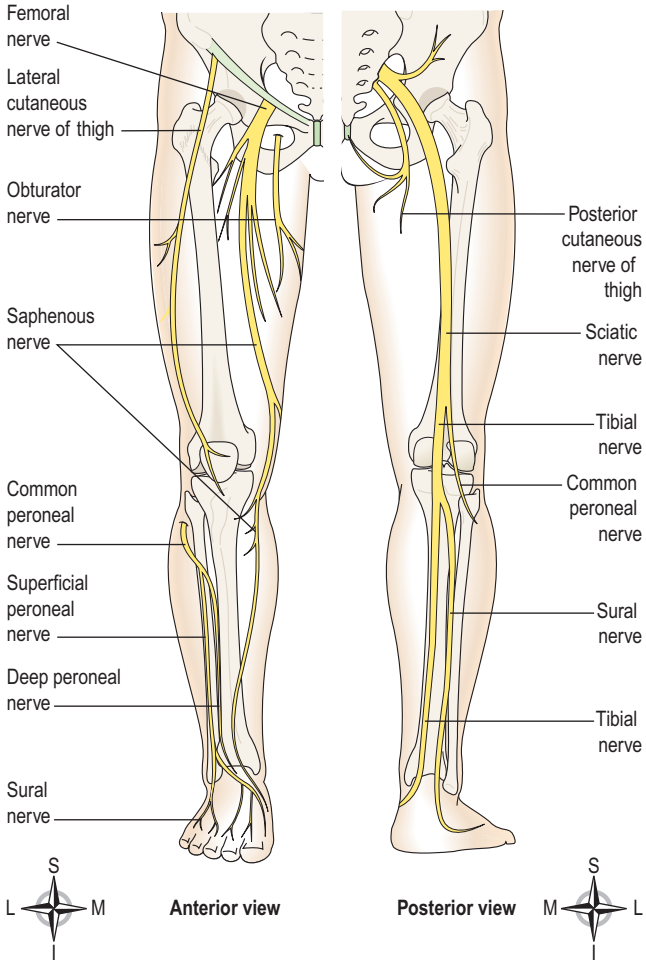

Figure 7.38 The main nerves of the leg.

Thoracic nerves

The thoracic nerves *do not* intermingle to form plexuses. There are 12 pairs and the first 11 are the *intercostal nerves*. They pass between the ribs supplying them, the intercostal muscles and overlying skin. The 12th pair comprises the *subcostal nerves*. The 7th–12th thoracic nerves also supply the muscles and the skin of the posterior and anterior abdominal walls.

Cranial nerves (Fig. 7.40) 7.10

There are 12 pairs of cranial nerves originating from nuclei in the inferior surface of the brain, some sensory, some motor and some mixed. Their names suggest their distribution or function, which, in the main, is generally related to the head and neck. They are numbered using Roman numerals according to the order they connect to the brain, starting anteriorly. They are:

I. Olfactory: sensory
II. Optic: sensory
III. Oculomotor: motor
IV. Trochlear: motor
V. Trigeminal: mixed
VI. Abducens: motor
VII. Facial: mixed
VIII. Vestibulocochlear (auditory): sensory
IX. Glossopharyngeal: mixed
X. Vagus: mixed
XI. Accessory: motor
XII. Hypoglossal: motor.

I. Olfactory nerves (sensory)

These are the nerves of the *sense of smell*. Their sensory receptors and nerve fibres originate in the upper part of the mucous membrane of the nasal cavity, pass upwards through the cribriform plate of the ethmoid bone and then pass to the *olfactory bulb* (see Fig. 8.23, p. 206). The nerves then proceed backwards as the olfactory tract, to the area for the perception of smell in the temporal lobe of the cerebrum (Ch. 8).

II. Optic nerves (sensory)

These are the nerves of the *sense of sight*. Their fibres originate in the retinae of the eyes and they combine to form the optic nerves (see Fig. 8.13, p. 199). They are directed backwards and medially through the posterior part of the orbital cavity. They then pass through the *optic foramina* of the sphenoid bone into the cranial cavity and join at the *optic chiasma*. The nerves proceed backwards as the *optic tracts* to the *lateral geniculate bodies* of the thalamus. Impulses pass from there to the visual areas in the occipital lobes of the cerebrum and to the cerebellum. In the occipital lobe sight is perceived, and in the cerebellum the impulses from the eyes contribute to the maintenance of balance, posture and orientation of the head in space.

III. Oculomotor nerves (motor)

These nerves arise from nuclei near the cerebral aqueduct. They supply:

- four of the six extrinsic muscles, which move the eyeball, i.e. the *superior*, *medial* and *inferior recti* and the *inferior oblique muscle* (see Table 8.1, p. 204)
- the intrinsic (intraocular) muscles:
  - *ciliary muscles*, which alter the shape of the lens, changing its refractive power
  - *circular muscles* of the iris, which constrict the pupil
- the *levator palpebrae muscles*, which raise the upper eyelids.

IV. Trochlear nerves (motor)

These nerves arise from nuclei near the cerebral aqueduct. They supply the *superior oblique muscles* of the eyes.

V. Trigeminal nerves (mixed)

These nerves contain motor and sensory fibres and are among the largest of the cranial nerves. They are the

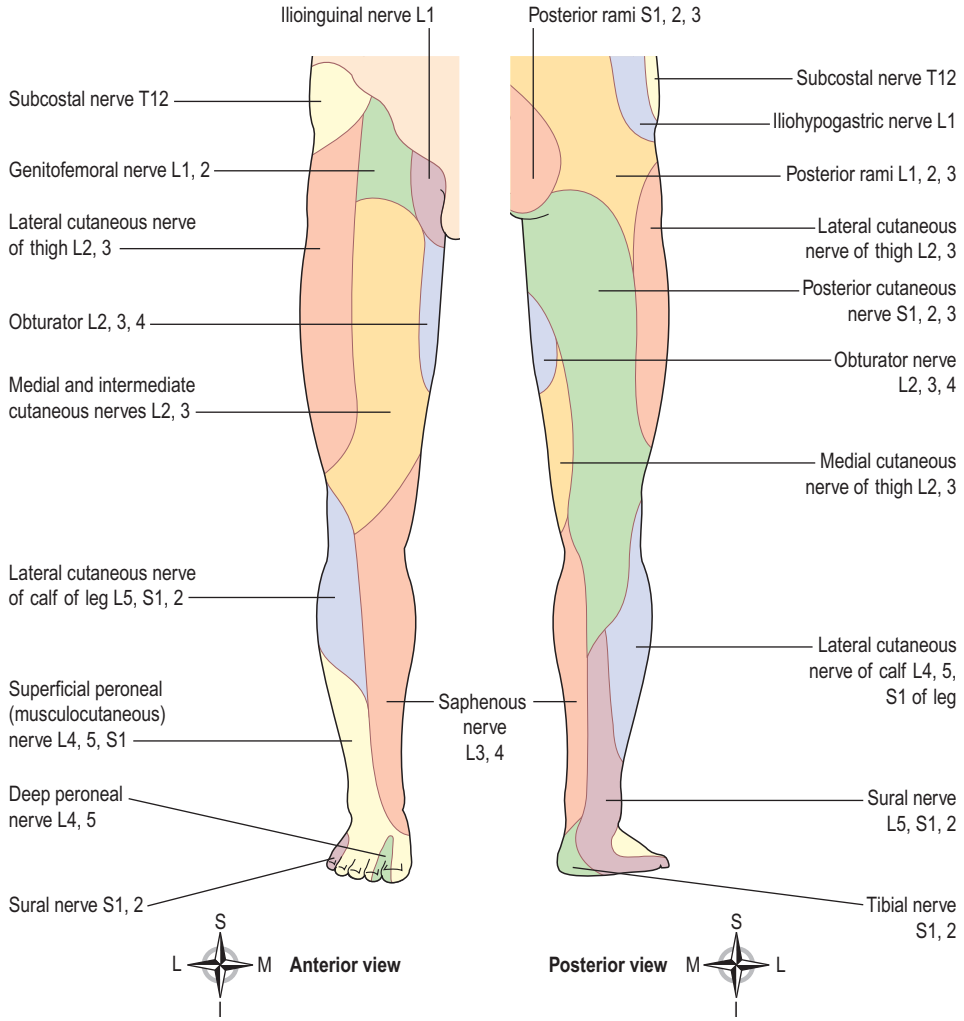

Figure 7.39 Distribution and origins of the cutaneous nerves of the leg. Colour distinguishes the dermatomes.

chief sensory nerves for the face and head (including the oral and nasal cavities and teeth), transmitting sensory impulses, e.g. for pain, temperature and touch. The motor fibres stimulate the muscles for chewing (mastication).

As the name suggests, there are three main branches of the trigeminal nerves. The dermatomes innervated by the sensory fibres on the right side are shown in Figure 7.41.

The ophthalmic nerves are sensory only and supply the lacrimal glands, conjunctiva of the eyes, forehead, eyelids, anterior aspect of the scalp and mucous membrane of the nose.

The maxillary nerves are sensory only and supply the cheeks, upper gums, upper teeth and lower eyelids.

The mandibular nerves contain both sensory and motor fibres. These are the largest of the three divisions and they supply the teeth and gums of the lower jaw, pinnae of the ears, lower lip and tongue. The motor fibres supply the muscles for chewing.

VI. Abducens nerves (motor)

These nerves arise from nuclei lying under the floor of the fourth ventricle. They supply the *lateral rectus muscles* of the eyeballs causing abduction, as the name suggests.

VII. Facial nerves (mixed)

These nerves are composed of both motor and sensory nerve fibres, arising from nuclei in the lower part of the pons. The motor fibres supply the muscles of facial expression. The sensory fibres convey impulses from the taste buds in the anterior two-thirds of the tongue to the taste perception area in the cerebral cortex (see Fig. 7.20).

VIII. Vestibulocochlear (auditory) nerves (sensory)

These nerves are composed of two divisions, the vestibular nerves and cochlear nerves.

The vestibular nerves arise from the semicircular canals of the inner ear and convey impulses to the cerebellum. They are associated with the maintenance of posture and balance.

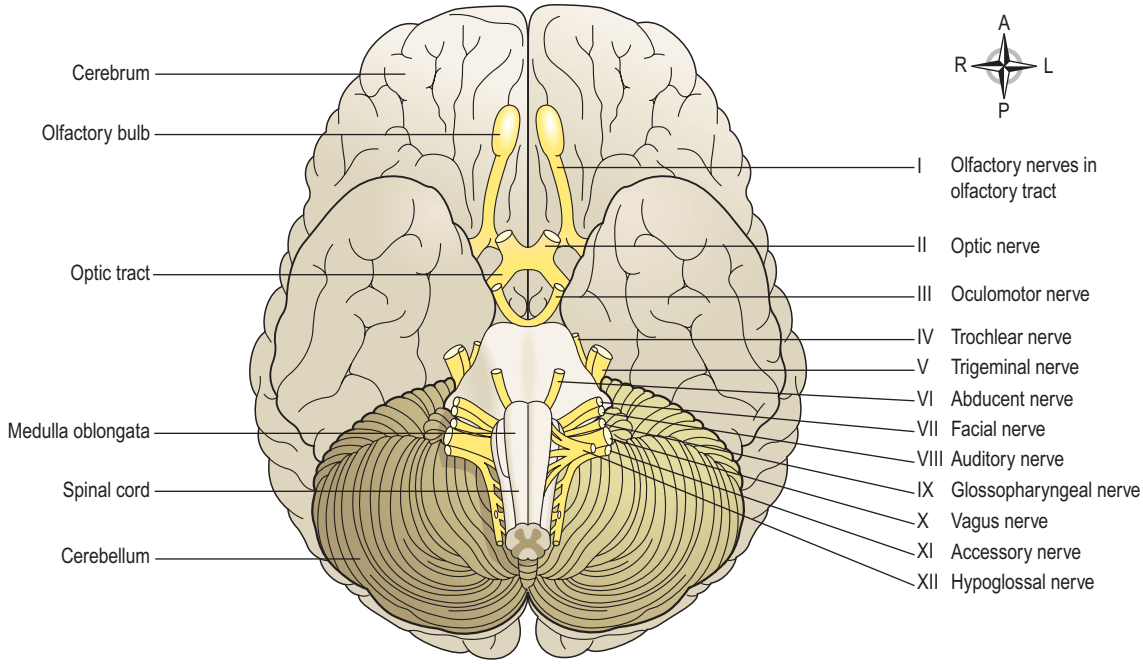

Figure 7.40 The inferior surface of the brain showing the cranial nerves and associated structures.

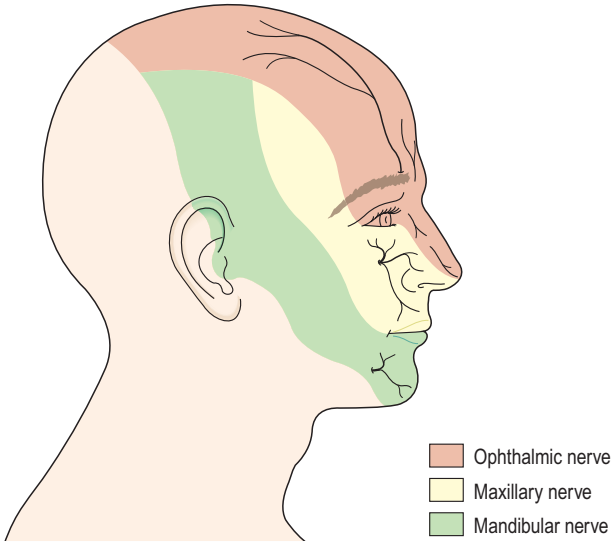

Figure 7.41 The cutaneous distribution of the main branches of the right trigeminal nerve.

The cochlear nerves originate in the spiral organ (of Corti) in the inner ear and convey impulses to the hearing areas in the cerebral cortex where sound is perceived.

IX. Glossopharyngeal nerves (mixed)

The motor fibres arise from nuclei in the medulla oblongata and stimulate the muscles of the tongue and pharynx and the secretory cells of the parotid (salivary) glands.

The sensory fibres convey impulses to the cerebral cortex from the posterior third of the tongue, the tonsils and pharynx and from taste buds in the tongue and pharynx. These nerves are essential for the swallowing and gag reflexes. Some fibres conduct impulses from the carotid sinus, which plays an important role in the control of blood pressure (p. 97).

X. Vagus nerves (mixed) (Fig. 7.42)

These nerves have the most extensive distribution of the cranial nerves; their name aptly means 'wanderer'. They pass downwards through the neck into the thorax and the abdomen. These nerves form an important part of the parasympathetic nervous system (see Fig. 7.44).

The motor fibres arise from nuclei in the medulla and supply the smooth muscle and secretory glands of the pharynx, larynx, trachea, bronchi, heart, carotid body, oesophagus, stomach, intestines, exocrine pancreas, gall bladder, bile ducts, spleen, kidneys, ureter and blood vessels in the thoracic and abdominal cavities.

The sensory fibres convey impulses from the membranes lining the same structures to the brain.

XI. Accessory nerves (motor)

These nerves arise from nuclei in the medulla oblongata and in the spinal cord. The fibres supply the *sternocleidomastoid* and *trapezius muscles*. Branches join the vagus nerves and supply the *pharyngeal* and *laryngeal muscles* in the neck.

XII. Hypoglossal nerves (motor)

These nerves arise from nuclei in the medulla oblongata. They supply the muscles of the tongue and muscles surrounding the hyoid bone and contribute to swallowing and speech.

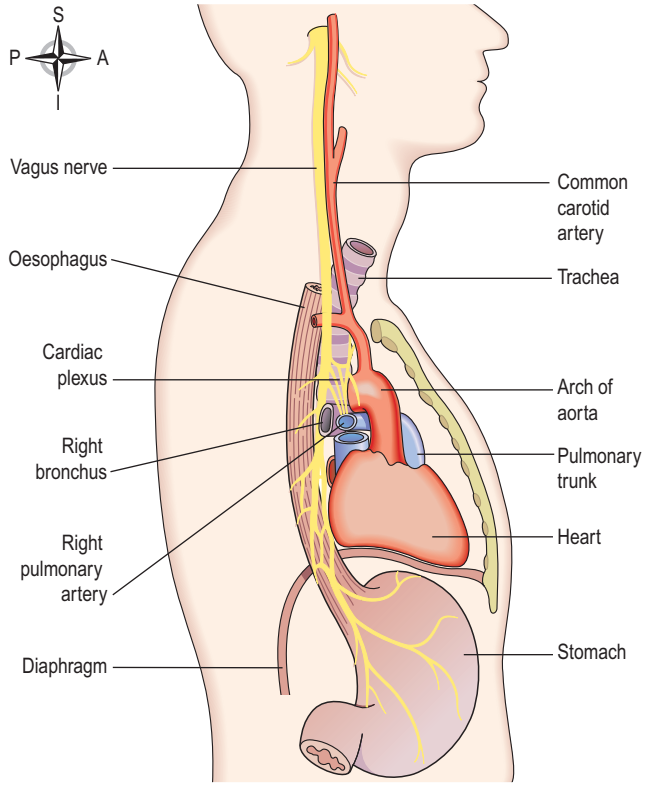

Figure 7.42 The position of the vagus nerve in the thorax viewed from the right side.

Autonomic nervous system 7.11, 7.12, 7.13

The autonomic or involuntary part of the nervous system (Fig. 7.1) controls involuntary body functions. Although stimulation does not occur voluntarily, the individual can sometimes be conscious of its effects, e.g. an increase in their heart rate.

The autonomic nervous system is separated into two divisions:

- *sympathetic* (thoracolumbar outflow)
- *parasympathetic* (craniosacral outflow).

The two divisions work in an integrated and complementary manner to maintain involuntary functions and homeostasis. Such activities include coordination and control of breathing, blood pressure, water balance, digestion and metabolic rate. Sympathetic activity predominates in stressful situations as it equips the body to respond when exertion and exercise is required. Parasympathetic activity is increased (and sympathetic activity is normally lessened) when digestion and restorative body activities predominate. There are similarities and differences between the two divisions. Some similarities are outlined in this section before the descriptions of the two divisions below.

As with other parts of the nervous system, the effects of autonomic activity are rapid. The effector organs are:

- *smooth muscle*, which controls the diameter of smaller airways and blood vessels
- *cardiac muscle*, which controls the rate and force of cardiac contraction
- *glands* that control the volumes of gastrointestinal secretions.

The *efferent (motor) nerves* of the autonomic nervous system arise from the brain and emerge at various levels between the midbrain and the sacral region of the spinal cord. Many of them travel within the same nerve sheath as peripheral nerves to reach the organs they innervate.

Each division has two efferent neurones between the central nervous system and effector organs. These are:

- *the preganglionic neurone*
- *the postganglionic neurone.*

The cell body of the preganglionic neurone is in the brain or spinal cord. Its axon terminals synapse with the cell body of the postganglionic neurone in an *autonomic ganglion* outside the CNS. The postganglionic neurone conducts impulses to the effector organ.

Sympathetic nervous system

Since the preganglionic neurones originate in the spinal cord at the thoracic and lumbar levels, the alternative name of 'thoracolumbar outflow' is apt (Fig. 7.43).

The preganglionic neurone. This has its cell body in the *lateral column of grey matter* in the spinal cord between the levels of the 1st thoracic and 2nd or 3rd lumbar vertebrae. The nerve fibre of this cell leaves the cord by the anterior root and terminates at a synapse in one of the ganglia either in the *lateral chain of sympathetic ganglia* or passes through it to one of the *prevertebral ganglia* (see below). Acetylcholine is the neurotransmitter at sympathetic ganglia.

The postganglionic neurone. This has its cell body in a ganglion and terminates in the organ or tissue supplied. Noradrenaline (norepinephrine) is usually the neurotransmitter at sympathetic effector organs. The major exception is that there is no parasympathetic supply to the sweat glands, the skin and blood vessels of skeletal muscles. These structures are supplied by only sympathetic postganglionic neurones, which are known as *sympathetic cholinergic nerves* and usually have acetylcholine as their neurotransmitter (see Fig. 7.8).

Sympathetic ganglia

The lateral chains of sympathetic ganglia. These chains extend from the upper cervical level to the sacrum, one chain lying on each side of the vertebral bodies. The ganglia are attached to each other by nerve fibres. Preganglionic neurones that emerge from the cord may synapse with the cell body of the postganglionic neurone at the

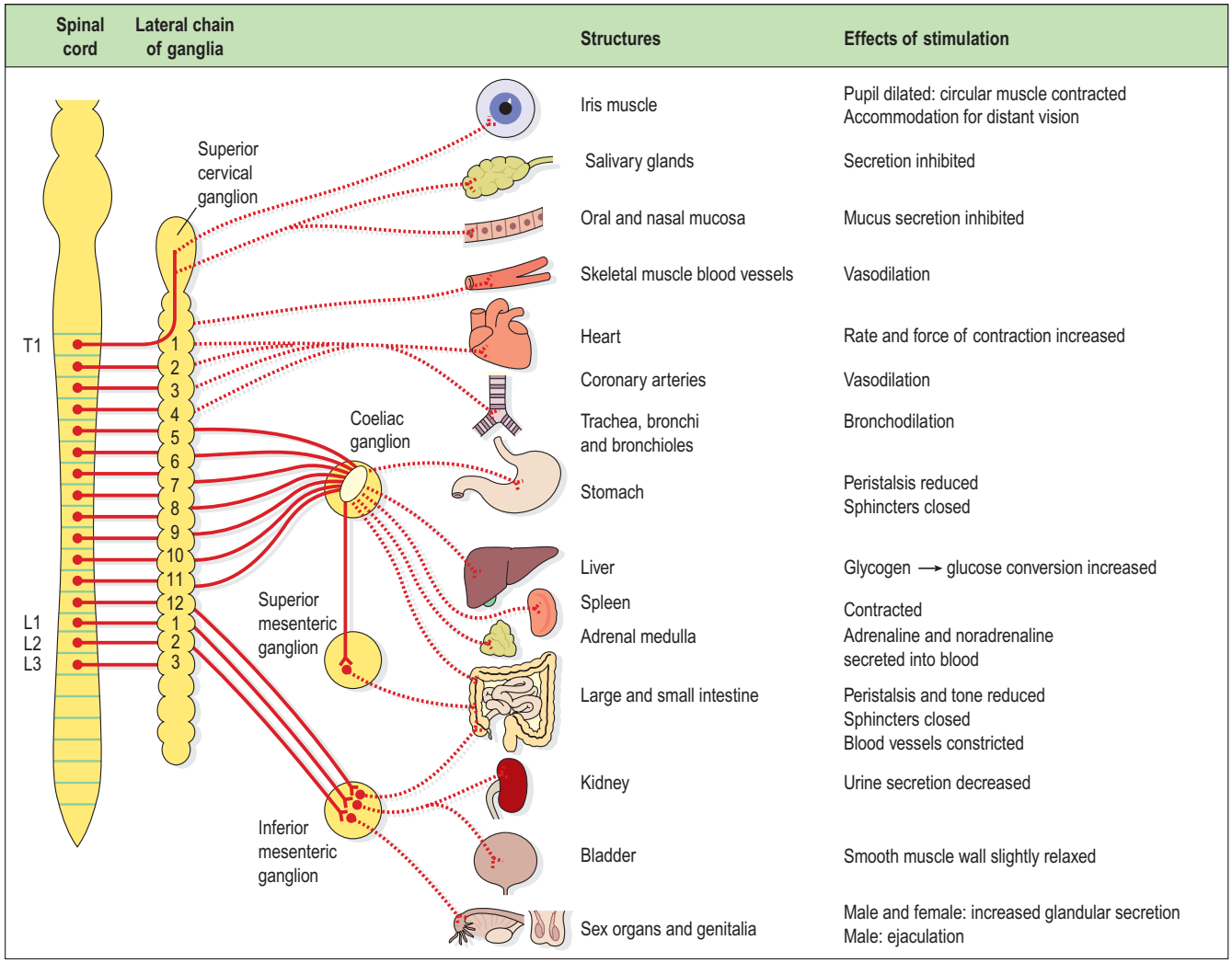

Figure 7.43 The sympathetic outflow, the main structures supplied and the effects of stimulation. Solid red lines – preganglionic fibres; broken lines – postganglionic fibres. There are right and left lateral chains of ganglia.

same level or they may pass up or down the chain through one or more ganglia before synapsing. For example, the nerve that dilates the pupil of the eye leaves the cord at the level of the 1st thoracic vertebra and passes up the chain to the superior cervical ganglion before it synapses with the cell body of the postsynaptic neurone. The postganglionic neurones then pass to the eyes.

The arrangement of the ganglia allows excitation of nerves at multiple levels very quickly, providing a rapid and widespread sympathetic response.

Prevertebral ganglia. There are three prevertebral ganglia situated in the abdominal cavity close to the origins of arteries of the same names:

- coeliac ganglion
- superior mesenteric ganglion
- inferior mesenteric ganglion.

The ganglia consist of nerve cell bodies rather diffusely distributed among a network of nerve fibres that form plexuses. Preganglionic sympathetic fibres pass through the lateral chain to reach these ganglia.

Parasympathetic nervous system

Like the sympathetic nervous system, two neurones (preganglionic and postganglionic) are involved in the transmission of impulses to the effector organs (Fig. 7.44). The neurotransmitter at both synapses is acetylcholine.

The preganglionic neurone. This is usually long in comparison to its counterpart in the sympathetic nervous system and has its cell body either in the brain or in the spinal cord. Those originating in the brain form the *cranial outflow* and are the cranial nerves III, VII, IX and X, arising from nuclei in the midbrain and brain stem. The cell bodies of the *sacral outflow* are in the lateral columns of grey matter at the distal end of the spinal cord. Their fibres leave the cord in sacral segments 2, 3 and 4. The nerve fibres of parasympathetic preganglionic neurones

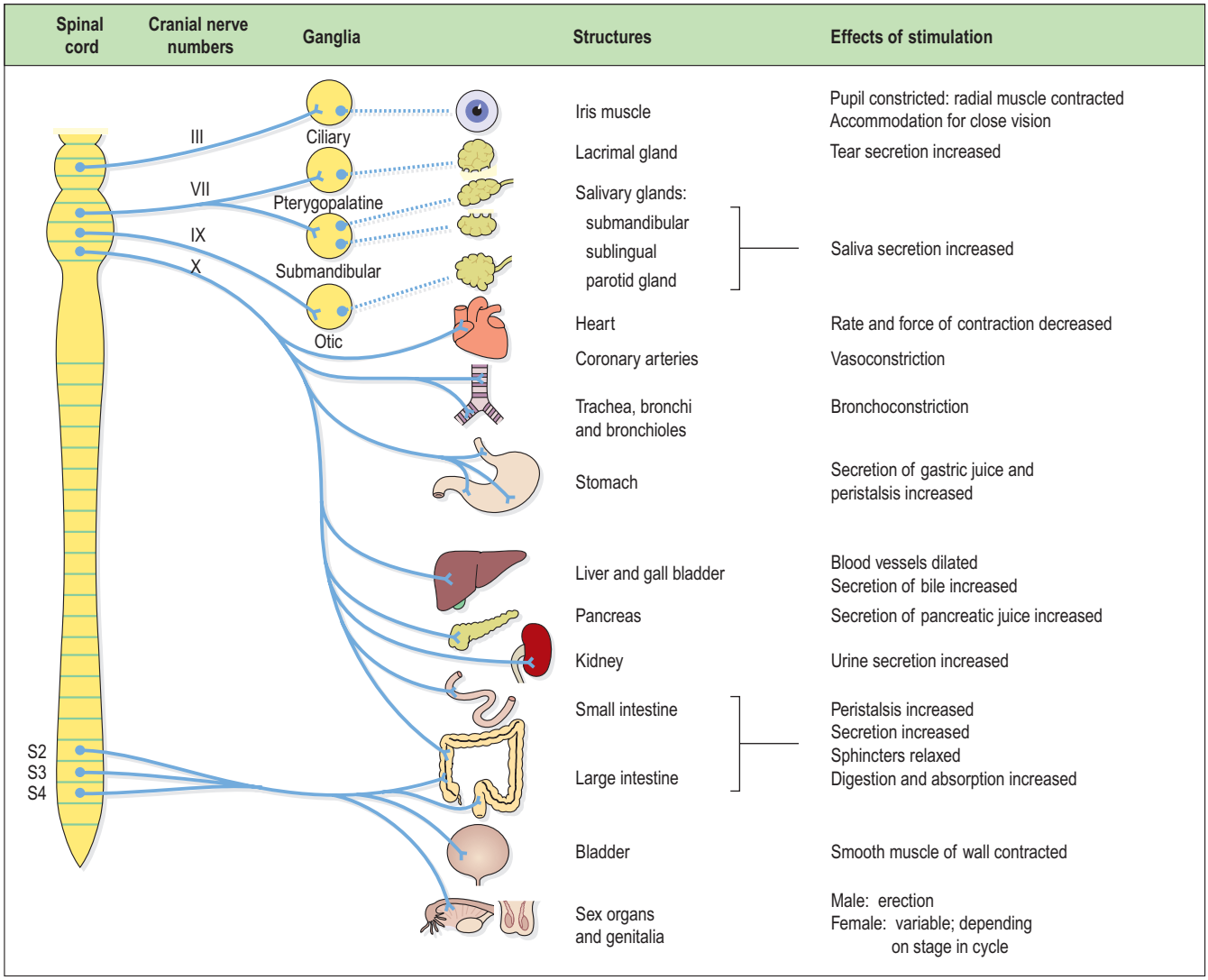

Figure 7.44 The parasympathetic outflow, the main structures supplied and the effects of stimulation. Solid blue lines – preganglionic fibres; broken lines – postganglionic fibres. Where there are no broken lines, the postganglionic neurone is in the wall of the structure.

usually synapse with their postganglionic counterparts at or near the effector organs.

The postganglionic neurone. This is usually very short and has its cell body either in a ganglion or, more often, in the wall of the organ supplied.

Functions of the autonomic nervous system

The autonomic nervous system is involved in many complex involuntary reflex activities which, like the reflexes described in earlier sections, depend not only on sensory input to the brain or spinal cord but also on motor output. In this case the reflex action is rapid contraction, or inhibition of contraction, of involuntary (smooth and cardiac) muscle or glandular secretion. These activities are coordinated subconsciously. Sometimes sensory input does reach consciousness and may result in temporary inhibition of the reflex action, e.g. reflex micturition can be inhibited temporarily.

The majority of the body organs are supplied by both sympathetic and parasympathetic nerves, which have complementary, and sometimes opposite effects that are finely balanced to ensure optimum functioning meets body needs at any moment.

Sympathetic stimulation prepares the body to deal with exciting and stressful situations, e.g. strengthening its defences in times of danger and in extremes of environmental temperature. A range of emotional states, e.g. fear, embarrassment and anger, also cause sympathetic stimulation. Sympathetic stimulation causes the adrenal glands to secrete the hormones adrenaline (epinephrine) and noradrenaline (norepinephrine) into the bloodstream. These hormones act as neurotransmitters when they reach target organs of the sympathetic nervous system. Through this effect, they potentiate and sustain the effects

of sympathetic stimulation. It is said that sympathetic stimulation mobilises the body for 'fight or flight'. The effects of stimulation on the heart, blood vessels and lungs (see below) enable the body to respond by preparing it for exercise. Additional effects are an increase in the metabolic rate and increased conversion of glycogen to glucose. During exercise, e.g. fighting or running away, when oxygen and energy requirements of skeletal muscles are greatly increased, these changes enable the body to respond quickly to meet the increased energy demand. **7.14**

Parasympathetic stimulation has a tendency to slow down cardiac and respiratory activity but it stimulates digestion and absorption of food and the functions of the genitourinary systems. Its general effect is that of a 'peace maker', allowing digestion and restorative processes to occur quietly and peacefully. **7.15**

Normally the two systems function together, maintaining a regular heartbeat, normal temperature and an internal environment compatible with both physiological needs and the immediate external surroundings.

Effects of autonomic stimulation

Cardiovascular system

Sympathetic stimulation

- Accelerates firing of the sinoatrial node in the heart, increasing the rate and force of the heartbeat.
- Dilates the coronary arteries, increasing the blood supply to cardiac muscle increasing the supply of oxygen and nutritional materials and the removal of metabolic waste products, thus increasing the capacity of the muscle to work.
- Dilates the blood vessels supplying skeletal muscle, with the same effects as those on cardiac muscle above.
- Raises peripheral resistance and blood pressure by constricting the small arteries and arterioles in the skin. In this way an increased blood supply is available for highly active tissue, such as skeletal muscle, heart and brain.
- Constricts the blood vessels in the secretory glands of the digestive system. This raises the volume of blood available for circulation in dilated blood vessels, e.g. cardiac muscle, skeletal muscles.
- Accelerates blood coagulation because of vasoconstriction.

Parasympathetic stimulation

- Decreases the rate and force of the heartbeat.
- Constricts the coronary arteries, reducing the blood supply to cardiac muscle.
- Blood vessels to skeletal muscles – no effect.

The parasympathetic nervous system exerts little or no effect on blood vessels except the coronary arteries.

Respiratory system

Sympathetic stimulation. This causes smooth muscle relaxation and therefore dilation of the airways (*bronchodilation*), especially the bronchioles, allowing a greater amount of air to enter the lungs at each inspiration, and increases the respiratory rate. In conjunction with the increased heart rate, the oxygen intake and carbon dioxide output of the body are increased to deal with 'fight or flight' situations.

Parasympathetic stimulation. This causes contraction of the smooth muscle in the airway walls, leading to *bronchoconstriction*.

Digestive and urinary systems

Sympathetic stimulation

- *The liver* increases conversion of glycogen to glucose, making more carbohydrate immediately available to provide energy.
- *The stomach* and *small intestine*. Smooth muscle contraction (peristalsis) and secretion of digestive juices are inhibited, delaying digestion, onward movement and absorption of food, and the tone of sphincter muscles is increased.
- *The adrenal (suprarenal) glands* are stimulated to secrete adrenaline (epinephrine) and noradrenaline (norepinephrine) which potentiate and sustain the effects of sympathetic stimulation throughout the body.
- *Urethral* and *anal sphincters*. The muscle tone of the sphincters is increased, inhibiting micturition and defecation.
- *The bladder* wall relaxes.
- *The metabolic rate* is greatly increased.

Parasympathetic stimulation

- *The liver*. The secretion of bile is increased.
- *The stomach* and *small intestine*. Motility and secretion are increased, together with the rate of digestion and absorption of food.
- *The pancreas*. The secretion of pancreatic juice is increased.
- *Urethral* and *anal sphincters*. Relaxation of the internal urethral sphincter is accompanied by contraction of the muscle of the bladder wall, and micturition occurs. Similar relaxation of the internal anal sphincter is accompanied by contraction of the muscle of the rectum, and defecation occurs. In both cases there is voluntary relaxation of the external sphincters.
- *The adrenal glands*. No effect.
- *The metabolic rate*. No effect.

Eye

Sympathetic stimulation. This causes contraction of the radiating muscle fibres of the iris, dilating the pupil. Retraction of the levator palpebrae muscles occurs, opening the eyes wide and giving the appearance of

alertness and excitement. The ciliary muscle that adjusts the thickness of the lens is slightly relaxed, facilitating distant vision.

Parasympathetic stimulation. This contracts the circular muscle fibres of the iris, constricting the pupil. The eyelids tend to close, giving the appearance of sleepiness. The ciliary muscle contracts, facilitating near vision.

Skin

Sympathetic stimulation

- Increases sweat secretion, leading to more loss of heat generated by increased skeletal muscle activity.
- Contracts the arrector pili (the muscles in the hair follicles of the skin), giving the appearance of 'goose flesh'.
- Constricts the peripheral blood vessels, increasing blood supply available to active organs, e.g. the heart and skeletal muscle.

There is no parasympathetic nerve supply to the skin. Some sympathetic fibres are adrenergic, causing vasoconstriction, and some are cholinergic, causing vasodilation (see Fig. 7.8, p. 149).

Afferent impulses from viscera

Sensory fibres from the viscera travel with autonomic fibres and are sometimes called *autonomic afferents*. The impulses they transmit are associated with:

- visceral reflexes, usually at an unconscious level, e.g. cough, blood pressure (baroreceptors)
- sensation of, e.g., hunger, thirst, nausea, sexual sensation, rectal and bladder distension
- visceral pain.

Visceral pain

Normally the viscera are insensitive to cutting, burning and crushing. However, a sensation of dull, poorly located pain is experienced when:

- visceral nerves are stretched
- a large number of fibres are stimulated
- there is ischaemia and local accumulation of metabolites
- the sensitivity of nerve endings to painful stimuli is increased, e.g. during inflammation.

If the cause of the pain, e.g. inflammation, affects the parietal layer of a serous membrane (pleura, peritoneum, see p. 45) the pain is acute and easily located over the site of inflammation. This is because the peripheral spinal (somatic) nerves that innervate the superficial tissues also innervate the parietal layer of serous membranes. They transmit the impulses to the cerebral cortex where somatic pain is perceived and accurately located. Appendicitis is an example of this type of pain. Initially it is dull and vaguely located around the midline of the abdomen. As the condition progresses the parietal peritoneum becomes involved and acute pain is clearly located in the right iliac fossa, i.e. over the appendix.

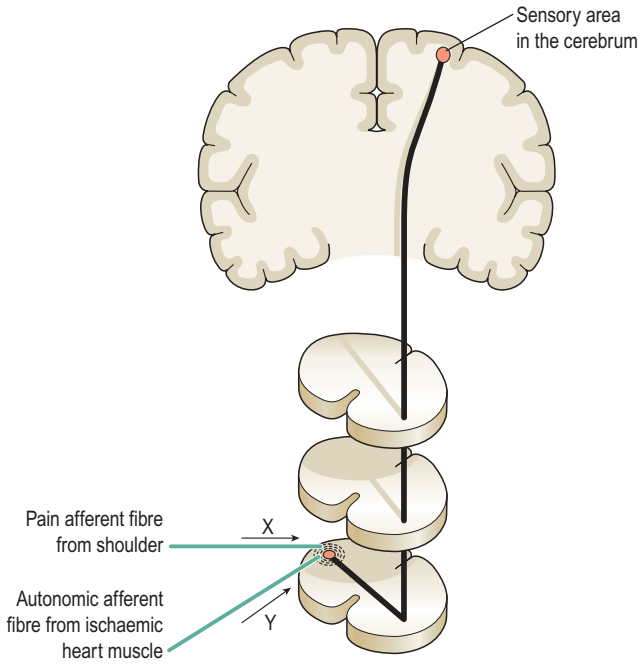

Figure 7.45 Referred pain. Ischaemic heart tissue generates impulses in nerve Y that then stimulate nerve X and pain is perceived in the shoulder.

Referred pain (Fig. 7.45)

In some cases of visceral disease, pain may be felt in superficial tissues remote from its site of origin, i.e. referred pain. This occurs when sensory fibres from the affected organ enter the same segment of the spinal cord as somatic nerves, i.e. those from the superficial tissues. It is believed that the sensory nerve from the damaged organ stimulates the closely associated nerve in the spinal cord and it transmits the impulses to the sensory area in the cerebral cortex where the pain is perceived as originating in the area supplied by the somatic nerve. Examples of referred pain are given in Table 7.3.

Effect of ageing on the nervous system

Learning outcome

After studying this section, you should be able to:

- Describe the effects of ageing on the nervous system.

Table 7.3 Referred pain

Tissue of origin of pain	Site of referred pain
Heart	Left shoulder
Liver, Biliary tract	Right shoulder
Kidney, Ureter	Loin and groin
Uterus	Low back
Male genitalia	Low abdomen
Prolapsed intervertebral disc	Leg

As neurones are not replaced after birth a natural decrease in numbers occurs with ageing; however, a considerable reserve means that cognitive function is not necessarily impaired. The brain of older adults is generally reduced in size and weighs less; the gyri become narrower and sulci wider. In older adults, *plaques,* accumulations of protein material, are often found around CNS neurones and *neurofibrillary tangles* may develop inside them, although their significance is unknown.

Decreased blood flow may develop in the arteries that supply the brain over a long period (*atheroma* and *arteriosclerosis,* Ch. 4) making their walls more prone to rupture. Should this occur, damage to the surrounding brain tissue causes the signs and symptoms of a *stroke* (p. 181).

Motor control of precise movement diminishes meaning that older adults take longer to carry out motor actions than younger adults and become more prone to falls. The conduction rate of nerve impulses becomes slower, and this may contribute to less effective control of, for example, vasodilation, vasoconstriction and the baroreceptor reflex (see Ch. 5).

Memory of the recent past typically becomes more difficult to access although long-term memories, including problem-solving skills, remain intact and generally remain retrievable. For unknown reasons, some older adults are much more incapacitated by progressive CNS changes than others, e.g. *dementia* (p. 183).

Effects of ageing on the special senses are almost universal and considered in Chapter 8. Thermoregulation is discussed in Chapter 14.

Disorders of the brain

Learning outcomes

After studying this section, you should be able to:

- list three causes of raised intracranial pressure (ICP)
- relate the effects of raised ICP to the functions of the brain and changes in vital signs
- outline how the brain is damaged during different types of head injury
- describe four complications of head injury
- explain the effects of cerebral hypoxia and stroke
- outline the causes and effects of dementia
- relate the pathology of Parkinson disease to its effects on body function.

Increased intracranial pressure

This is a serious complication of many conditions that affect the brain. The cranium forms a rigid cavity enclosing the brain, the cerebral blood vessels and cerebrospinal fluid (CSF). An increase in volume of any one of these will lead to raised intracranial pressure (ICP).

Sometimes its effects are more serious than the condition causing it, e.g. by disrupting the blood supply or distorting the shape of the brain, especially if the ICP rises rapidly. A slow rise in ICP allows time for compensatory adjustment to be made, i.e. a slight reduction in the volume of circulating blood and of CSF. The slower the rise in ICP, the more effective is the compensation.

Rising ICP is accompanied by bradycardia and hypertension. As it reaches its limit, a further small increase in pressure is followed by a sudden and usually serious reduction in the cerebral blood flow as autoregulation fails. The result is hypoxia and a rise in carbon dioxide levels, causing arteriolar dilation, which further increases ICP. This leads to rapid and progressive loss of functioning neurones, which exacerbates bradycardia and hypertension. Further cerebral hypoxia causes *vasomotor paralysis* and death.

The causes of increased ICP are described on the following pages and include:

- cerebral oedema
- hydrocephalus, the accumulation of excess CSF
- expanding lesions inside the skull, also known as space-occupying lesions e.g.:
  - haemorrhage or haematoma (traumatic or spontaneous)
  - tumours (primary or secondary).

Expanding lesions may occur in the brain or in the meninges and they can damage the brain in various ways (Fig. 7.46).

Effects of increased ICP

Displacement of the brain

Lesions causing displacement are usually one sided but may affect both sides. Such lesions may cause:

- *herniation* (displacement of part of the brain from its usual compartment) of the cerebral hemisphere between the corpus callosum and the free border of the falx cerebri on the same side
- herniation of the midbrain between the pons and the free border of the tentorium cerebelli on the same side
- compression of the subarachnoid space and flattening of the cerebral convolutions
- distortion of the shape of the ventricles and their ducts
- herniation of the cerebellum through the foramen magnum

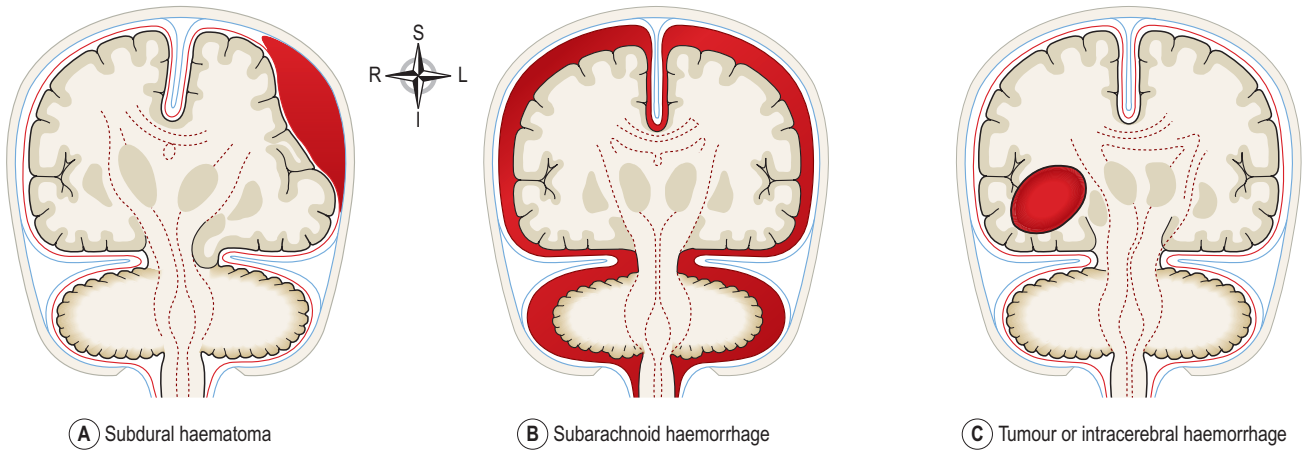

Figure 7.46 Effects of different types of expanding lesions inside the skull: A. Subdural haematoma. **B.** Subarachnoid haemorrhage. **C.** Tumour or intracerebral haemorrhage.

- protrusion of the medulla oblongata through the foramen magnum (‘*coning*’).

Obstruction of the flow of cerebrospinal fluid

The ventricles or their ducts may be displaced or a duct obstructed. The effects depend on the position of the lesion, e.g. compression of the cerebral aqueduct causes dilation of the lateral ventricles and the third ventricle, further increasing the ICP.

Vascular damage

Blood vessels may be stretched or compressed, causing:

- haemorrhage when stretched blood vessels rupture
- ischaemia and infarction due to compression of blood vessels
- *papilloedema* (oedema round the optic disc) due to compression of the retinal vein in the optic nerve sheath where it crosses the subarachnoid space.

Neural damage

The vital centres in the medulla oblongata may be damaged when the increased ICP causes ‘*coning*’. Stretching may damage cranial nerves, especially the oculomotor (III) and the abducens (VI), causing disturbances of eye movement and accommodation. Dilation of a pupil and loss of the light reflex (failure of the pupil to constrict in response to bright light) is caused by compression of the oculomotor nerve.

Bone changes

Prolonged increase of ICP causes bony changes, e.g.:

- erosion, especially of the sphenoid bone
- stretching and thinning in children before ossification is complete.

Cerebral oedema

Oedema (p. 125) occurs when there is excess fluid in tissue cells and/or interstitial spaces. In the brain, this is known as cerebral oedema and increases intracranial pressure. It is associated with:

- traumatic head injury
- haemorrhage
- infections, abscesses
- hypoxia, local ischaemia or infarcts
- tumours
- inflammation of the brain or meninges
- hypoglycaemia (p. 237).

Hydrocephalus

In this condition the volume of CSF is abnormally high and is usually accompanied by increased ICP. An obstruction to CSF flow is the most common cause. It is described as *communicating* when there is free flow of CSF from the ventricular system to the subarachnoid space and *non-communicating* when there is not, i.e. there is obstruction in the system of ventricles, foramina or ducts (see Fig. 7.15).

Enlargement of the head occurs in children when ossification of the cranial bones is incomplete but, in spite of this, the ventricles dilate and cause stretching and thinning of the brain. After ossification is complete, hydrocephalus leads to a marked increase in ICP and destruction of nervous tissue.

Head injuries

Damage to the brain may be serious even when there is no outward sign of injury. At the site of injury there may be:

- a scalp wound, with haemorrhage between scalp and skull bones
- damage to the underlying meninges and/or brain with local haemorrhage inside the skull
- a depressed skull fracture, causing local damage to the underlying meninges and brain tissue
- temporal bone fracture, creating an opening between the middle ear and the meninges
- fracture involving the air sinuses of the sphenoid, ethmoid or frontal bones, making an opening between the nose and the meninges.

Acceleration–deceleration injuries

Because the brain floats relatively freely in ‘a cushion’ of CSF, sudden acceleration or deceleration has an inertia effect. For example, when a vehicle stops suddenly passengers are thrown forward: the head then moves forwards or backwards relative to the rest of the body causing injury to the brain at the site of impact if it moves within the skull. In *‘contre coup’* injuries, brain damage is more severe on the side opposite to the site of impact. Other injuries include:

- nerve cell damage, usually to the frontal and parietal lobes, due to movement of the brain over the rough surface of bones of the base of the skull
- nerve fibre damage due to stretching, especially following rotational movement
- haemorrhage due to rupture of blood vessels in the subarachnoid space on the side opposite to the impact or many diffuse small haemorrhages, following rotational movement.

Complications of head injury

If the individual survives the immediate effects, complications may develop hours or days later. Sometimes they are the first indication of serious damage caused by a seemingly trivial injury. Their effects may increase

ICP, damage brain tissue or provide a route of entry for infection.

Traumatic intracranial haemorrhage

Haemorrhage may occur causing secondary brain damage at the site of injury, on the opposite side of the brain or diffusely throughout the brain. If bleeding continues, the expanding haematoma increases the ICP, compressing the brain. 7.16

Extradural haemorrhage. This may follow a direct blow that may or may not cause a fracture. The individual may recover quickly and indications of increased ICP typically appear only several hours later as the haematoma grows and the outer layer of dura mater (periosteum) is stripped off the bone. The haematoma grows rapidly when arterial blood vessels are damaged. In children fractures are rare because the skull bones are still soft and the joints (sutures) have not fused. The haematoma usually remains localised.

Acute subdural haemorrhage. This is due to haemorrhage from either small veins in the dura mater or larger veins between the layers of dura mater before they enter the venous sinuses. The blood may spread in the subdural space over one or both cerebral hemispheres (Fig. 7.46A). There may be concurrent subarachnoid haemorrhage (Fig. 7.46B), especially when there are extensive brain contusions and lacerations.

Chronic subdural haemorrhage. This may occur weeks or months after minor injuries and sometimes there is no history of injury. It occurs most commonly in people in whom there is some cerebral atrophy, e.g. older adults and in alcohol misuse. Evidence of increased ICP may be delayed when brain volume is reduced. The haematoma gradually increases in size owing to repeated small haemorrhages and causes mild chronic inflammation and accumulation of inflammatory exudate. In time it is isolated by a wall of fibrous tissue.

Intracerebral haemorrhage and cerebral oedema. These occur following contusions, lacerations and shearing injuries associated with acceleration and deceleration, especially rotational movements.

Cerebral oedema (p. 180) is a common complication of contusions of the brain, leading to increased ICP, hypoxia and further brain damage.

Meningitis

(see p. 184).

Post-traumatic epilepsy

This is characterised by seizures (fits) and may develop in the first week or several months after injury. Early development is most common after severe injuries, although in children the injury itself may have appeared trivial. After depressed fractures or large haematomas, epilepsy tends to develop later.

Vegetative states

This condition is a consequence of severe cortical brain damage. The individual appears awake and is observed to undergo sleep–wake cycles; however, there are no signs of awareness or responses to the external environment. As the brain stem remains intact, the vital centres continue to function i.e. breathing and blood pressure are maintained. It is considered permanent if there is no recovery 12 months after trauma or longer than 6 months after any other cause.

Cerebral hypoxia

Hypoxia may be due to disturbances in the autoregulation of blood supply to the brain or conditions affecting cerebral blood vessels.

When the mean blood pressure falls below about 60 mmHg, the autoregulating mechanisms that control the blood flow to the brain by adjusting the diameter of the arterioles fail. The consequent rapid decrease in the cerebral blood supply leads to hypoxia and lack of glucose. If severe hypoxia is sustained for more than a few minutes there is irreversible brain damage. Neurones are affected first, then the neuroglial cells and later the meninges and blood vessels. Conditions in which autoregulation breaks down include:

- cardiorespiratory arrest
- sudden severe hypotension
- carbon monoxide poisoning
- hypercapnia (excess blood carbon dioxide)
- drug overdosage with, e.g., opioid analgesics, hypnotics.

Conditions affecting cerebral blood vessels that may lead to hypoxia include:

- occlusion of a cerebral artery by, e.g., a rapidly expanding intracranial lesion, atheroma, thrombosis or embolism (Ch. 5)
- arterial stenosis that occurs in arteritis, e.g. polyarteritis nodosa, syphilis, diabetes mellitus, degenerative changes in older adults.

If the individual survives the initial episode of ischaemia, then infarction, necrosis and loss of function of the affected area of brain may occur.

Stroke

Cerebrovascular disease is the underlying cause of most strokes and transient ischaemic attacks. Predisposing factors include:

- hypertension
- atheroma
- diabetes mellitus
- cigarette smoking.

Stroke is a very common cause of death and disability in older adults. The incidence is greater in Asian and black African populations, and increases steeply with age. Effects appear in a few minutes and include paralysis of a limb or one side of the body (*hemiparesis*) often accompanied by disturbances of speech and vision. The nature and extent of damage depend on the location of the affected blood vessels. By definition, signs and symptoms of a stroke last for longer than 24 hours. The vast majority are caused by cerebral infarction (about 85%) with spontaneous intracranial haemorrhage accounting for most of the remainder.

In contrast to a stroke, a *transient ischaemic attack* (TIA) is a brief period of reversible cerebral deficit. Typically there is a short period (minutes or hours) where there is weakness of a limb, loss of speech and/or vision followed by complete recovery. A TIA may precede a stroke (about 30% in 5 years) or, less commonly, myocardial infarction (see Ch. 5). The arbitrary definition of a TIA lasting under 24 hours is no longer used.

Around 80% of patients survive for at least a month following an acute stroke; gradual improvement of limb movement follows in about 50% of cases, which is sometimes accompanied by improved speech. Recurrence is common.

Cerebral infarction 7.17

This occurs when blood flow to the brain is suddenly interrupted resulting in cerebral hypoxia. The main cause is atheroma affecting the carotid artery or aortic arch, which is complicated by thrombosis (p. 119) although a blocked artery supplying the brain can also arise from an embolus originating in the heart, e.g. infective endocarditis (p. 128).

Spontaneous intracranial haemorrhage

The haemorrhage may be into the subarachnoid space or intracerebral (Fig. 7.47). It is commonly associated with an aneurysm or hypertension. In each case the escaped blood may cause arterial spasm, leading to ischaemia, infarction, fibrosis (gliosis) and hypoxic brain damage. A severe haemorrhage may be instantly fatal while repeated small haemorrhages have a cumulative effect in extending brain damage (*multi-infarct dementia*).

Intracerebral haemorrhage. Prolonged hypertension leads to the formation of multiple microaneurysms in the walls of very small arteries in the brain. Rupture of one or more of these, due to continuing rise in blood pressure, is usually the cause of intracerebral haemorrhage. The most common sites are branches of the middle cerebral artery in the region of the internal capsule and the basal ganglia.

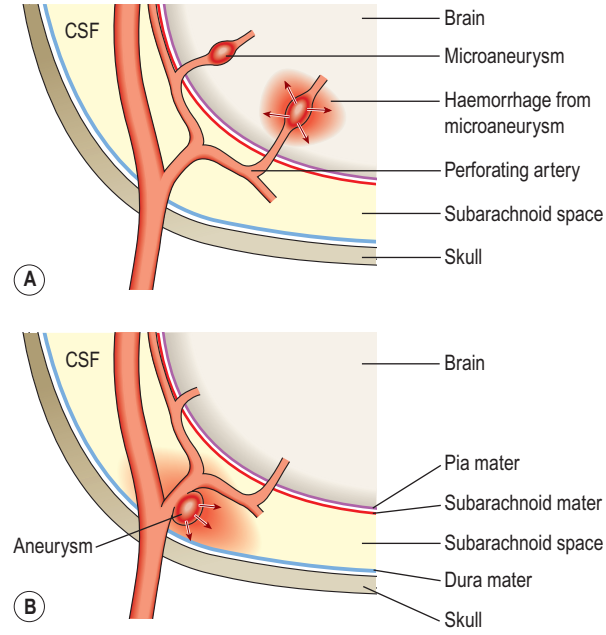

Figure 7.47 Types of haemorrhage causing stroke: **A.** Intracerebral. **B.** Subarachnoid.

Severe haemorrhage causes compression and destruction of tissue, a sudden increase in ICP and distortion and herniation of the brain. Death follows when the vital centres in the medulla oblongata are damaged by haemorrhage or if there is coning due to increased ICP.

Less severe haemorrhage causes paralysis and loss of sensation of varying severity, affecting the side of the body opposite the haemorrhage. If the bleeding stops and does not recur, a fluid-filled cyst develops, i.e. the haematoma is walled off by gliosis, the blood clot is gradually absorbed and the cavity becomes filled with tissue exudate. When the ICP returns to normal, some function may be restored, e.g. speech and movement of limbs.

Subarachnoid haemorrhage. This accounts for a small number of strokes and is usually due to rupture of a berry aneurysm on one of the major cerebral arteries, or less often bleeding from a congenitally malformed blood vessel (Fig. 7.47B). The blood may remain localised but usually spreads in the subarachnoid space round the brain and spinal cord, causing a general increase in ICP without distortion of the brain (Fig. 7.46B). The irritant effect of the blood may cause arterial spasm, leading to ischaemia, infarction, gliosis and the effects of localised brain damage. It occurs most commonly in middle life, but occasionally in young people owing to rupture of a malformed blood vessel. This condition is often fatal or results in permanent disability.

Dementia

Dementia is caused by progressive, irreversible degeneration of the cerebral cortex and results in mental deterioration, usually over several years. There is gradual impairment of memory (especially short term), intellect and reasoning but consciousness is not affected. Emotional lability and personality change may also occur.

Alzheimer disease

This condition is the commonest form of dementia in developed countries. The aetiology is unknown although genetic factors may be involved. Females are affected twice as often as males and it usually affects those over 60 years, the incidence increasing with age. It commonly affects people with Down syndrome by the age of 40 years. There is progressive atrophy of the cerebral cortex accompanied by deteriorating mental functioning. Death usually occurs between 2 and 8 years after onset.

Huntington disease

This usually manifests itself between the ages of 30 and 50 years. It is inherited as an autosomal dominant disorder (see p. 443) associated with deficient production of the neurotransmitter gamma aminobutyric acid (GABA). By the time of onset, the individual may have already passed the genetic abnormality on to their children. Extrapyramidal changes cause chorea, rapid uncoordinated jerking movements of the limbs and involuntary twitching of the facial muscles. As the disease progresses, cortical atrophy causes personality changes and dementia.

Secondary dementias

Dementia may occur in association with other conditions:

- vascular dementia, also known as *multi-infarct dementia,* which may accompany cerebrovascular disease
- toxic – e.g. alcohol and solvent misuse and, less often, vitamin B deficiencies
- tumours – usually metastases but sometimes primary intracranial tumours
- metabolic (e.g. uraemia, liver failure) and endocrine (e.g. hypothyroidism)
- infections, although these are less common e.g. syphilis, human immunodeficiency virus (HIV) and Creutzfeldt–Jakob Disease (CJD).

Parkinson disease 7.18

In this disease there is gradual and progressive degeneration of dopamine releasing neurones in the extrapyramidal system especially at the basal ganglia. This leads to lack of control and coordination of muscle movement resulting in:

- slowness of movement (bradykinesia) and difficulty initiating movements
- fixed muscle tone causing expressionless facial features, rigidity of voluntary muscles causing the slow and characteristic stiff shuffling gait and stooping posture
- muscle tremor of extremities that usually begins in one hand, e.g. 'pill rolling' movement of the fingers
- speech problems, excessive salivation and, in advanced disease, dysphagia.

Onset is usually between 45 and 60 years; with more men than women affected. The cause is usually unknown but some cases are associated with repeated trauma as in, e.g., 'punch drunk' boxers; tumours causing midbrain compression; drugs, e.g. phenothiazines; heavy metal poisoning. There is progressive physical disability but the intellect is not impaired (Fig. 7.48).

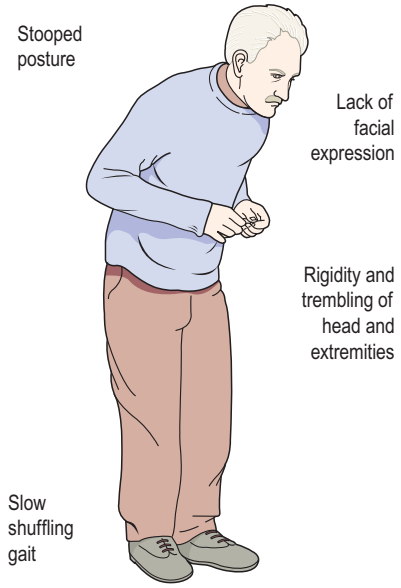

Figure 7.48 Typical posture of Parkinson disease.

Effects of poisons on the brain

Many chemicals, including drugs, environmental toxins, microbial products and metabolic wastes can damage nervous tissue. This may range from short-term reversible neurological disturbance, e.g. depression of cognitive and motor functions after drinking alcohol, through to long-term permanent damage, for example heavy metal poisoning (e.g. lead) or hepatic encephalopathy (p. 334).

Infections of the central nervous system

Learning outcome

After studying this section, you should be able to:

- describe common infections of the nervous system and their effects on body function.

The brain and spinal cord are relatively well protected from microbial infection by the blood–brain barrier.

CNS infections are usually bacterial or viral but may also be protozoal or fungal. Infections may originate in the meninges (*meningitis*) or in the brain (*encephalitis*), then spread from one site to the other.

Bacterial infections

Entry of bacteria into the CNS may be:

- direct – through a compound skull fracture or through the skull bones from, e.g., middle ear or paranasal sinus infections, mastoiditis
- blood-borne – from infection elsewhere in the body, e.g. septicaemia, bacterial endocarditis (p. 128)
- iatrogenic – introduced during an invasive procedure, e.g. lumbar puncture.

Bacterial meningitis

The term 'meningitis' usually refers to inflammation of the subarachnoid space and is most commonly transmitted through contact with an infected individual. Bacterial meningitis is usually preceded by a mild upper respiratory tract infection during which a few bacteria enter the bloodstream and are carried to the meninges. Common microbes include:

- *Haemophilus influenzae* in children between the ages of 2 and 5 years
- *Neisseria meningitidis* in those between 5 and 30 years, the most common type
- *Streptococcus pneumoniae* in people over 30 years.

Other pathogenic bacteria can also cause meningitis, e.g. those causing tuberculosis (p. 268) and syphilis.

Meningitis can also affect the dura mater, especially when spread is direct through a compound skull fracture as leakage of CSF and blood from the site also provides a route of entry for microbes. CSF and blood may escape through the:

- skin, in compound skull fractures
- middle ear, in fractures of the temporal bone (*CSF otorrhoea*)
- nose, in fractures of the sphenoid, ethmoid or frontal bones when air sinuses are involved (*CSF rhinorrhoea*).

It may also arise from nearby infections, e.g., of the ear. If an extradural or subdural abscess forms, the infection may spread further locally should it rupture.

The onset is usually sudden with severe headache, neck stiffness, photophobia (intolerance of bright light) and fever. This is sometimes accompanied by a petechial rash. CSF appears cloudy owing to the presence of many bacteria and neutrophils. Mortality and morbidity rates are considerable.

Viral infections

Entry of viruses into the CNS is usually blood-borne from viral infection elsewhere in the body and, less commonly, through the nervous system. In the latter situation, *neurotropic viruses*, i.e. those with an affinity for nervous tissue, travel along peripheral nerve from a site elsewhere, e.g. poliovirus. They enter the body via:

- the alimentary tract, e.g. poliomyelitis
- the respiratory tract, e.g. shingles
- skin abrasions, e.g. rabies.

The effects of viral infections vary according to the site and the amount of tissue destroyed. Viruses may damage neurones by multiplying within them or stimulating an immune reaction which may explain why signs of some infections do not appear until there is a high antibody titre, 1–2 weeks after infection.

Viral meningitis

This is the most common form of meningitis, which is usually relatively mild and followed by complete recovery.

Viral encephalitis

Viral encephalitis is rare and usually associated with a recent viral infection. Most cases are mild and recovery is usually complete. More serious cases are usually associated with rabies or *Herpes simplex* viruses. Many different sites can be affected and, as neurones cannot be replaced, loss of function reflects the extent of damage. In severe infections neurones and neuroglia may be affected, followed by necrosis and gliosis. If the individual survives the initial acute phase there may be residual dysfunction, e.g. cognitive impairment and epilepsy. If vital centres in the medulla are involved the condition can be fatal.

Herpes zoster (shingles)

Herpes zoster viruses cause chickenpox (varicella), mainly in children, and shingles (zoster) in adults. Susceptible children may contract chickenpox from a person with shingles but not the reverse. Infected adults may show no immediate signs of disease. The viruses may remain dormant in posterior root ganglia of the spinal nerves then become active years later, causing shingles. Reactivation may be either spontaneous or associated with

intercurrent illness or depression of the immune system, e.g. by drugs, old age, AIDS.

The posterior root ganglion becomes acutely inflamed. From there the viruses travel along the sensory nerve to the surface tissues supplied, e.g. skin, cornea. The infection is usually unilateral and the most common sites are:

- nerves supplying the trunk, sometimes two or three adjacent dermatomes
- the ophthalmic division of the trigeminal nerve (Fig. 7.41), causing *trigeminal neuralgia*, and, if vesicles form on the cornea, there may be ulceration, scarring and residual interference with vision.

Affected tissues become inflamed and vesicles, containing serous fluid and viruses, develop along the course of the nerve. This is accompanied by persistent pain and hypersensitivity to touch (*hyperaesthesia*). Recovery is usually slow and there may be some loss of sensation, depending on the severity of the disease.

Poliomyelitis

This disease is usually caused by *polioviruses* and, occasionally, by other *enteroviruses*. The infection is spread by food contaminated by infected faecal matter and, initially, viral multiplication occurs in the alimentary tract. The viruses are then blood-borne to the nervous system and invade anterior horn cells in the spinal cord. Usually there is a mild febrile illness with no indication of nerve damage. In mild cases there is complete recovery but there is permanent disability in many others. Irreversible damage to lower motor neurones (p. 163) causes muscle paralysis which, in the limbs, may lead to deformity because of the unopposed tonal contraction of antagonistic muscles. Death may occur owing to respiratory paralysis if the intercostal muscles are affected. Vaccination programmes have now almost eradicated this disease in developed countries.

Rabies

All warm-blooded animals are susceptible to the rabies virus, which is endemic in many countries but not in the UK. The main reservoirs of this virus are wild animals, some of which may be carriers. When these infect domestic pets they then become the source of human infection. The viruses multiply in the salivary glands and are present in large numbers in saliva. They enter the body through skin abrasions and are believed to travel to the brain along peripheral nerves. The incubation period varies from about 2 weeks to several months, possibly reflecting the distance viruses travel between the site of entry and the brain. There is acute encephalomyelitis with extensive damage to the basal ganglia, midbrain and medulla oblongata. Involvement of the posterior root ganglia of the peripheral nerves causes meningeal irritation, extreme hyperaesthesia, muscle spasm and convulsions. *Hydrophobia* (hatred of water) and overflow of saliva from the mouth are due to painful spasm of the throat muscles that inhibits swallowing. In the advanced stages muscle spasm may alternate with flaccid paralysis and death is usually due to respiratory muscle spasm or paralysis.

Not all people exposed to the virus contract rabies, but in those who do, the mortality rate is high.

Human immunodeficiency virus (HIV)

The brain is often affected in individuals with AIDS (p. 386) resulting in opportunistic infection (e.g. meningitis) and dementia.

Creutzfeldt–Jakob disease

This infective condition may be caused by a 'slow' virus, the nature and transmission of which is poorly understood. It is thought to be via a heat-resistant transmissible particle known as a *prion protein*. It is a rapidly progressive form of dementia (p. 183) for which there is no known treatment so the condition is always fatal.

Myalgic encephalitis (ME)

This condition is also known as post-viral syndrome or chronic fatigue syndrome. It affects mostly teenagers and young adults and the aetiology is unknown. Sometimes the condition follows a viral illness. The effects include malaise, severe fatigue, poor concentration and myalgia. Recovery is usually spontaneous but sometimes results in chronic disability.

Demyelinating diseases

Learning outcome

After studying this section, you should be able to:

- explain how the signs and symptoms of demyelinating disease are related to pathological changes in the nervous system.

These diseases are caused either by injury to axons or by disorders of cells that secrete myelin, i.e. oligodendrocytes and Schwann cells.

Multiple sclerosis (MS)

In this disease areas of demyelinated white matter, called plaques, replace myelin. They are irregularly distributed throughout the brain and spinal cord. Grey matter in the brain and spinal cord may also be affected because of the arrangement of satellite oligodendrocytes round cell bodies. In the early stages there may be little damage to axons.

It usually develops between the ages of 20 and 40 years and affects twice as many women as men. The actual cause(s) of MS are not known but several factors seem to

be involved. It appears to be an autoimmune disorder, possibly triggered by a viral infection, e.g. measles.

Environment before adolescence is implicated because the disease is most prevalent in people who spend their pre-adolescent years in temperate climates, and those who move to other climates after that age retain their susceptibility to MS. People from equatorial areas moving into a temperate climate during adolescence or later life appear not to be susceptible.

Genetic factors are implicated too as there is an increased incidence of MS among siblings, especially identical twins, and parents of patients.

Effects of multiple sclerosis

Symptoms depend on the size and location of the developing plaques and include:

- weakness of skeletal muscles and sometimes paralysis
- loss of coordination and movement
- disturbed sensation, e.g. burning or pins and needles
- incontinence of urine
- visual disturbances, especially blurring and double vision. The optic nerves are commonly affected early in the disease.

The disease pattern is usually one of relapses and remissions of widely varying duration. Each relapse causes further loss of nervous tissue and progressive dysfunction. In some cases there may be chronic progression without remission, or acute disease rapidly leading to death.

Acute disseminated encephalomyelitis

This is a rare but serious condition that may occur as a complication of a viral infection, e.g. measles, chickenpox, or rarely following primary immunisation against viral diseases, mainly in older children and adults.

The cause of the acute diffuse demyelination is not known. It has been suggested that an autoimmune effect on myelin is triggered either by viruses during viral infection such as measles, or by an immune response to vaccines. The effects vary considerably, according to the distribution and degree of demyelination and are similar to those of MS. The early febrile state may progress to paralysis and coma. Most patients survive the initial phase and recover completely but some have severe neurological impairment.

Diseases of the spinal cord

Learning outcome

After studying this section, you should be able to:

- explain how disorders of the spinal cord cause abnormal function.

Because space in the neural canal and intervertebral foramina is limited, any condition that distorts their shape or reduces the space may damage the spinal cord or peripheral nerve roots, or compress blood vessels causing ischaemia. Such conditions include:

- fracture and/or dislocation of vertebrae
- tumours of the meninges or vertebrae
- prolapsed intervertebral disc.

The effects of disease or injury depend on the severity of the damage, the type and position of the neurones involved.

Motor neurones

Table 7.4 gives a summary of the effects of damage to the motor neurones. The parts of the body affected depend on which neurones have been damaged and their site in the brain, spinal cord or peripheral nerve.

Upper motor neurone (UMN) lesions

Lesions of the UMNs above the level of the decussation of the pyramids affect the opposite side of the body, e.g. haemorrhage or infarction in the internal capsule of one hemisphere causes paralysis of the opposite side of the body. Lesions below the decussation affect the same side of the body. The lower motor neurones are released from cortical control and muscle tone is increased (Table 7.4).

Lower motor neurone (LMN) lesions

The cell bodies of LMNs are in the spinal cord and the axons are part of peripheral nerves. Lesions of LMNs lead to weakness or paralysis and atrophy of the effector muscles they supply.

Motor neurone disease

This is a chronic progressive degeneration of upper and lower motor neurones, occurring more commonly in men over 50 years of age. The cause is seldom known, although a few cases are inherited as an autosomal dominant disorder (p. 443). Motor neurones in the cerebral cortex, brain stem and anterior horns of the spinal cord are

Table 7.4 Summary of effects of damage to motor neurones

Upper motor neurone	Lower motor neurone
Muscle weakness and spastic paralysis	Muscle weakness and flaccid paralysis
Exaggerated tendon reflexes	Absence of tendon reflexes
Muscle twitching	Muscle wasting Contracture of muscles Impaired circulation

destroyed and replaced by gliosis. Early effects are usually weakness and twitching of the small muscles of the hand, and muscles of the arm and shoulder girdle. The legs are affected later. Death occurs within 3–5 years and is usually due to respiratory difficulties or complications of immobility.

Mixed motor and sensory conditions

Subacute combined degeneration of the spinal cord

This condition most commonly occurs as a complication of pernicious anaemia (p. 74). Vitamin B_{12} is needed for the formation and maintenance of myelin by Schwann cells and oligodendrocytes. Although degeneration of the spinal cord may be apparent before the anaemia, it is arrested by treatment with vitamin B_{12}.

The degeneration of myelin occurs in the posterior and lateral columns of white matter in the spinal cord, especially in the upper thoracic and lower cervical regions. Less frequently the changes occur in the posterior root ganglia and peripheral nerves. Demyelination of proprioceptor fibres (sensory) leads to ataxia and involvement of upper motor neurones leads to increased muscle tone and spastic paralysis. Without treatment, death may occur within 5 years.

Compression of the spinal cord and nerve roots

The causes include:

- prolapsed intervertebral disc
- syringomyelia
- tumours: metastatic, meningeal or nerve sheath
- fractures with displacement of bone fragments.

Prolapsed intervertebral disc (Fig. 7.49)

This is the most common cause of compression of the spinal cord and/or nerve roots. The vertebral bodies are separated by the intervertebral discs, each consisting of an outer rim of cartilage, the *annulus fibrosus*, and a central core of soft gelatinous material, the *nucleus pulposus*.

Prolapse of a disc is herniation of the nucleus pulposus, causing the annulus fibrosus and the posterior longitudinal ligament to protrude into the neural canal. It is most common in the lumbar region, usually below the level of the spinal cord, i.e. below L2, and therefore affects nerve roots only. If it occurs in the cervical region, the cord may also be compressed. Herniation may occur suddenly, typically in young adults during strenuous exercise or exertion, or progressively in older people when there is bone disease or degeneration of the disc, which leads to rupture during minimal exercise. The hernia may be:

- one sided, causing pressure damage to a nerve root
- midline, compressing the spinal cord, the anterior spinal artery and possibly bilateral nerve roots.

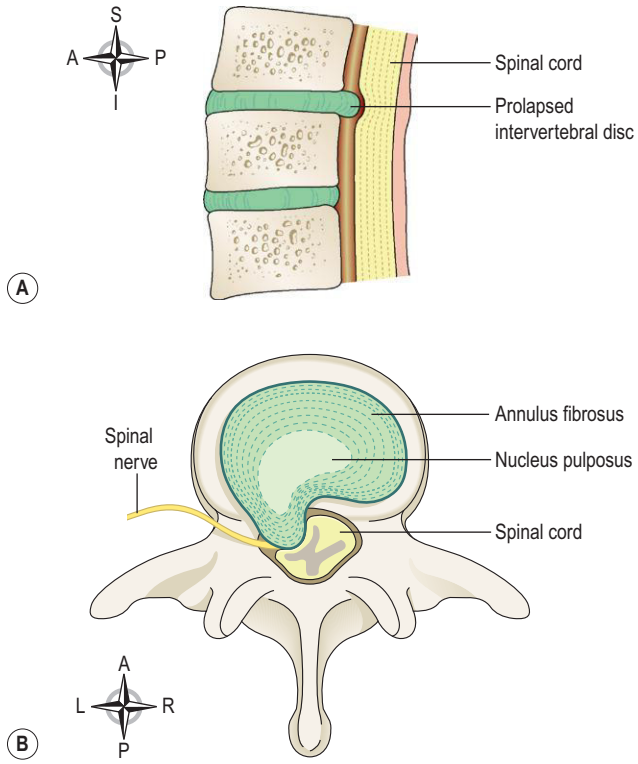

Figure 7.49 Prolapsed intervertebral disc. A. Viewed from the side. **B.** Viewed from above.

The outcome depends upon the size of the hernia and the length of time the pressure is applied. Small herniations cause local pain due to pressure on the nerve endings in the posterior longitudinal ligament. Large herniations may cause:

- unilateral or bilateral paralysis
- acute or chronic pain perceived to originate from the area supplied by the compressed sensory nerve, e.g. in the leg or foot
- compression of the anterior spinal artery, causing ischaemia and possibly necrosis of the spinal cord
- local muscle spasm due to pressure on motor nerves.

Syringomyelia

This dilation (syrinx) of the central canal of the spinal cord occurs most commonly in the cervical region and is associated with congenital abnormality of the distal end of the fourth ventricle. As the central canal dilates, pressure causes progressive damage to sensory and motor neurones.

Early effects include *dissociated anaesthesia*, i.e. insensibility to heat and pain, due to compression of the sensory fibres that cross the cord immediately they enter. In the long term there is destruction of motor and sensory tracts, leading to spastic paralysis and loss of sensation and reflexes.

Diseases of peripheral nerves

Learning outcomes

After studying this section, you should be able to:

- compare and contrast the causes and effects of polyneuropathies and mononeuropathies
- describe the effects of Guillain–Barré syndrome and Bell's palsy.

Peripheral neuropathy

This is a group of diseases of peripheral nerves not associated with inflammation. They are classified as:

- polyneuropathy: several nerves are affected
- mononeuropathy: a single nerve is usually affected.

Polyneuropathy

Damage to a number of nerves and their myelin sheaths occurs in association with other disorders, e.g.:

- vitamin deficiencies, e.g. vitamins B_1, B_6, B_{12}
- metabolic disorders, e.g. diabetes mellitus, uraemia (in renal failure), hepatic failure, malignancy
- toxic reactions to, e.g., alcohol, lead, mercury, aniline dyes and some drugs, such as phenytoin, isoniazid.

Long nerves are usually affected first, e.g. those supplying the feet and legs. The outcome depends upon the cause of the neuropathy and the extent of the damage.

Mononeuropathy

Usually only one nerve is damaged and the most common cause is ischaemia due to pressure. The resultant dysfunction depends on the site and extent of the injury. Examples include:

- pressure applied to cranial nerves in cranial bone foramina due to distortion of the brain by increased ICP
- compression of a nerve in a confined space caused by surrounding inflammation and oedema, e.g. the median nerve in carpal tunnel syndrome (see p. 435)
- external pressure on a nerve, e.g. an unconscious person lying with an arm hanging over the side of a bed or trolley
- compression of the axillary (circumflex) nerve by ill-fitting crutches
- trapping of a nerve between the broken ends of a bone
- ischaemia due to thrombosis of blood vessels supplying a nerve.

Guillain–Barré syndrome

Also known as acute inflammatory polyneuropathy, this is sudden, acute, progressive, bilateral ascending muscular weakness or paralysis. It begins in the lower limbs and spreads to the arms, trunk and cranial nerves. It usually occurs 1–3 weeks after an upper respiratory tract infection. There is widespread inflammation accompanied by some demyelination of spinal, peripheral and cranial nerves and the spinal ganglia. Paralysis may affect all the limbs and the respiratory muscles. Patients who survive the acute phase usually recover completely in weeks or months.

Bell's palsy

Compression of a facial nerve in the temporal bone foramen causes paralysis of facial muscles with drooping and loss of facial expression on the affected side. The immediate cause is inflammation and oedema of the nerve. The underlying cause is thought to be viral. The onset may be sudden or develop over several hours. Distortion of the features is due to muscle tone on the unaffected side, the affected side being expressionless. Recovery is usually complete within 3–8 weeks although the condition is sometimes permanent.

Developmental abnormalities of the nervous system

Learning outcomes

After studying this section, you should be able to:

- describe developmental abnormalities of the nervous system
- relate their effects to abnormal body function.

Spina bifida

This is a congenital malformation of the embryonic neural tube and spinal cord (Fig. 7.50). The vertebral (neural) arches are absent and the dura mater is abnormal, most commonly in the lumbosacral region. The causes are not known, although the condition is associated with dietary deficiency of folic acid at the time of conception. These neural tube defects may be of genetic origin or due to environmental factors, e.g. irradiation, or maternal infection (rubella) at a critical stage in development of the fetal vertebrae and spinal cord. The effects depend on the extent of the abnormality.

Occult spina bifida

In this 'hidden' condition the skin over the defect is intact and excessive growth of hair over the site may be the only sign of abnormality. This is sometimes associated with minor nerve defects that commonly affect the bladder.

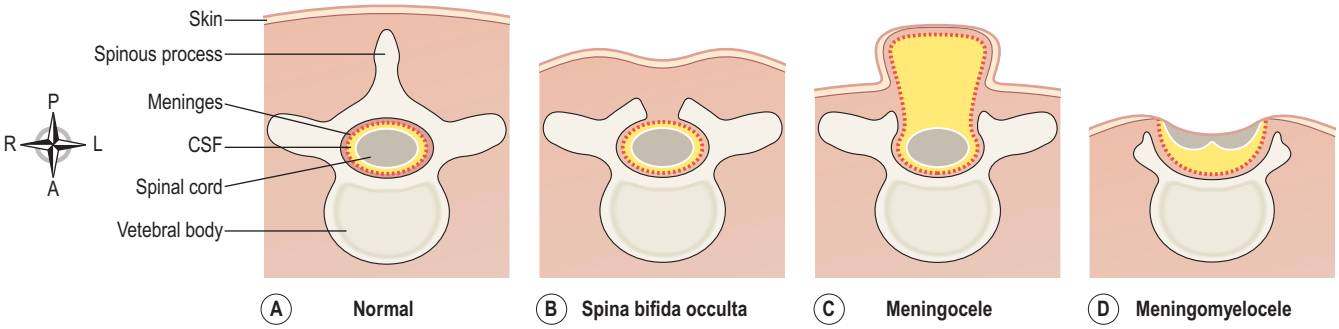

Figure 7.50 Spina bifida. Vertebrae viewed from above.

Meningocele

The skin over the defect is very thin and may rupture after birth. There is dilation of the subarachnoid space posteriorly. The spinal cord is correctly positioned.

Meningomyelocele

The meninges and spinal cord are grossly abnormal. The skin may be absent or rupture. In either case there is leakage of CSF, and the meninges may become infected. Serious nerve defects result in paraplegia and lack of sphincter control causing incontinence of urine and faeces. There may also be mental impairment.

Hydrocephalus

(see p. 180.)

Tumours of the nervous system

Learning outcome

After studying this section, you should be able to:

- outline the effects of tumours of the nervous system.

Some 50% of brain tumours are metastases from the other primary sites, often the bronchus, breast, stomach or prostate (see below).

Primary tumours of the nervous system usually arise from the neuroglia, meninges or blood vessels. Neurones are rarely involved because they do not normally multiply. Nervous tissue tumours rarely metastise. Because of this, the rate of growth of an intracranial tumour is more important than the likelihood of spread outside the nervous system. In this context, 'benign' means slow growing and 'malignant' rapid growing. Early signs typically include headache, vomiting, visual disturbances and *papilloedema* (swelling of the optic disc seen by ophthalmoscopy). Signs of raised ICP appear after the limits of compensation have been reached (see p. 179).

Within the confined space of the skull, haemorrhage within a tumour exacerbates the increased ICP caused by the tumour.

Slow-growing tumours

These allow time for compensation for increasing intracranial pressure, so the tumour may be quite large before its effects are evident. Compensation involves gradual reduction in the volume of cerebrospinal fluid and circulating blood.

Rapidly growing tumours

These do not allow time for adjustment to compensate for the rapidly increasing ICP, so the effects quickly become apparent (Fig. 7.46C). Complications include:

- neurological impairment, depending on tumour site and size
- effects of increased ICP (p. 179)
- necrosis of the tumour, causing haemorrhage and oedema.

Specific tumours

Brain tumours typically arise from different cells in adults and children, and may range from benign to highly malignant. The most common tumours in adults are *glioblastomas* and *meningiomas*, which are usually benign and originate from arachnoid granulations. *Astrocytomas* and *medulloblastomas* account for most brain tumours in children.

Metastases in the brain

The prognosis of this condition is poor and the effects depend on the site(s) and rate of growth of metastases. There are two forms: discrete multiple tumours, mainly in the cerebrum, and diffuse tumours in the arachnoid mater.

For a range of self-assessment exercises on the topics in this chapter, visit Evolve online resources: https://evolve.elsevier.com/Waugh/anatomy/