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Arterial Supply to the Central Nervous System

Arterial Supply to the Brain

1.1 Basic Pattern of the Main Arteries Supplying the Brain

Five pairs of arteries supply the brain (Figure 1.1). The more rostral four of these arise from the **cerebral arterial circle,** popularly known as the circle of Willis, on the ventral surface of the brain; the cerebral arterial circle roughly circumscribes the hypothalamus, with the stalk of the hypophysis (pituitary gland) in its centre. The fifth and most caudal arises from the basilar artery. The five pairs of arteries are:

1) the **rostral cerebral artery**;
2) the **middle cerebral artery**, this being the largest cerebral artery in most mammals;
3) the **caudal cerebral artery**;
4) the **rostral cerebellar artery**; and
5) the **caudal cerebellar artery**.

There are also various smaller arteries, which supply the medulla oblongata and pons.

Although there are minor species variations, these vessels occur in mammals consistently. The cerebellar arteries are variable in number and origin even within the same species: for example, in man and the horse, the rostral one may arise from the basilar artery. The three cerebral arteries are remarkably constant in amphibians and higher forms generally.

1.2 Basic Pattern of Incoming Branches to the Cerebral Arterial Circle

There are four potential incoming arterial channels to the cerebral arterial circle in mammals generally (Figure 1.2):

1) **internal carotid artery**;
2) **basilar artery**: This midline artery is a continuation rostrally of the ventral spinal artery. However, the blood that flows within the ventral spinal and basilar arteries has come from the vertebral artery via the segmental spinal arteries.

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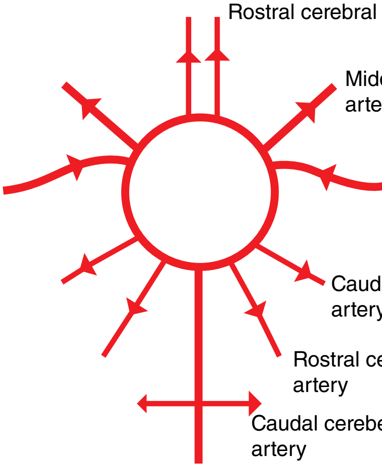

Figure 1.1 Diagram of the cerebral arterial circle and its outgoing branches. The connection across the midline at the rostral end of the circle is inconstant in the dog and ruminants.

3) **maxillary artery**: This artery supplies the arterial circle by its so-called anastomosing ramus, which joins the maxillary artery to the internal carotid artery.
4) **vertebral artery**: The vertebral artery connects to the internal carotid artery, and in some species it supplies the arterial circle directly by this route. However, it may also supply the circle indirectly via the ventral spinal artery and therefore the basilar artery (see above).

Because of the anatomy of these four arterial channels, the blood which distributes itself over the brain may be **internal carotid blood, maxillary blood**, or **vertebral blood**, or a combination of these (Figure 1.3).

1.3 Species Variations

In no domestic mammals are all four of these potential arterial channels to the cerebral arterial circle fully developed. Some of the channels are reduced in calibre or are even totally obliterated. The direction of flow in the remaining channels depends on the pressure gradients within the various vessels. The general relationships of these gradients have been worked out experimentally, thus establishing the direction of flow and the distribution of blood in each species. The following account applies to the intact live animal.

1.3.1 Dog, Man and most Mammals

Most mammals have what appears to be the most usual mammalian pattern of arterial supply to the brain (Figure 1.3(a)). The blood reaching the rostral half of the brain is internal carotid blood, but the caudal half of the brain is supplied by vertebral blood. This is because the pressure gradients are such that the flow of blood in the basilar artery is **rostral**. Consequently, vertebral blood reaches not only the cerebellar arteries but also the caudal cerebral artery.

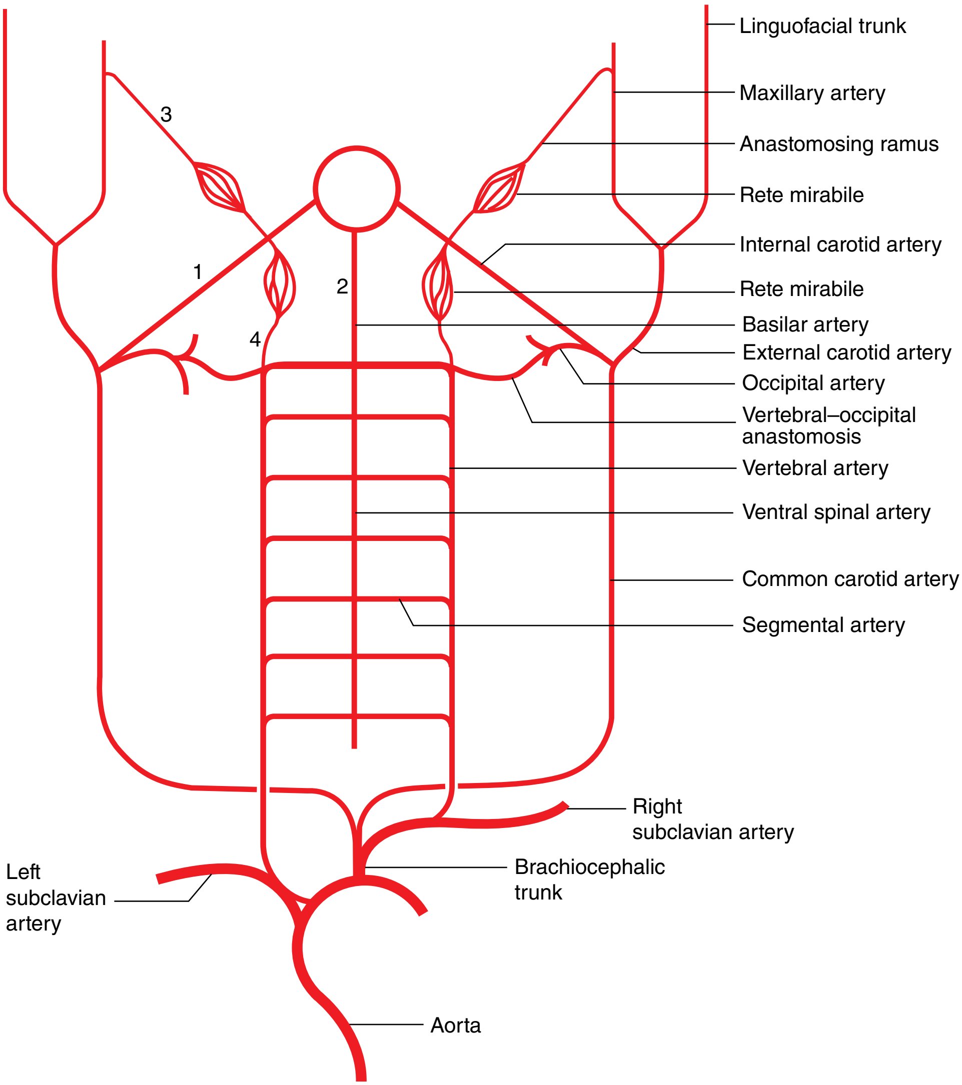

Figure 1.2 Diagram showing the potential arterial channels to the cerebral arterial circle. There are four such channels, numbered 1 to 4 on the left: 1 = the internal carotid artery; 2 = the basilar artery; 3 = the anastomosing ramus from the maxillary artery to the internal carotid artery; and 4 = the connection of the vertebral artery to the internal carotid artery.

The anastomosing ramus of the maxillary artery is much reduced in these species. In the dog there is an anastomotic artery which connects the internal carotid to the external ophthalmic artery, the latter being a branch of the maxillary artery; this anastomosis could possibly provide a supply to the arterial circle. In man, the maxillary artery anastomoses with the internal carotid via the sphenopalatine artery and also via the middle meningeal artery.

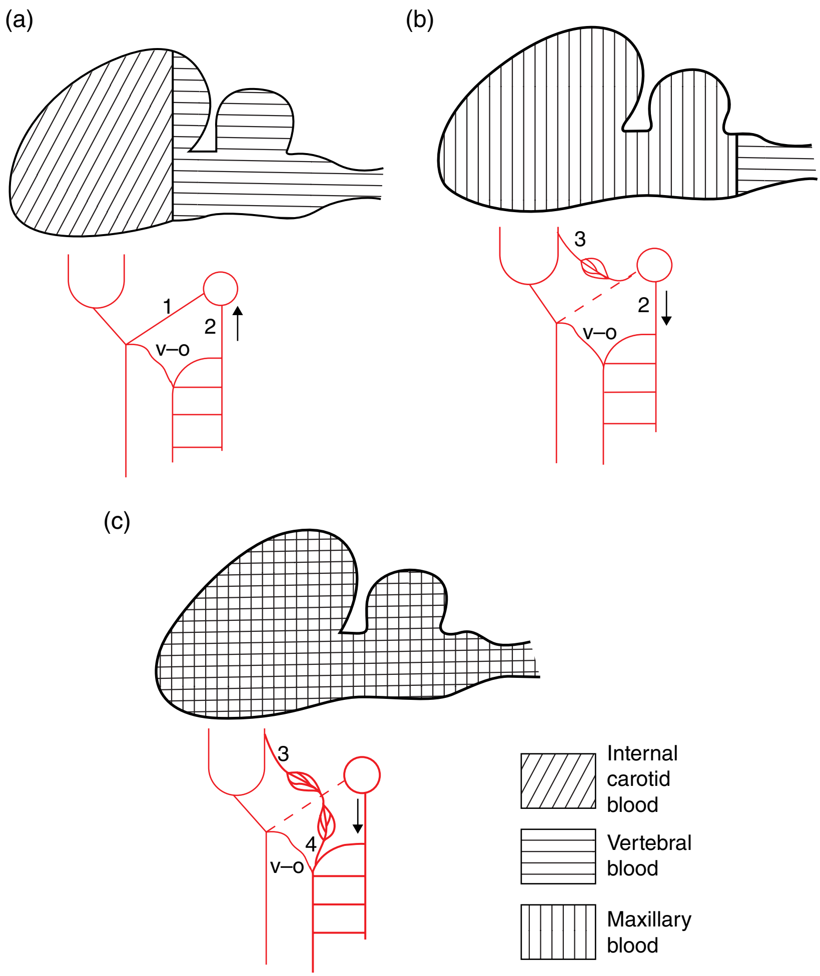

Figure 1.3 Diagrams showing species variations in the sources of arterial blood to the brain. In each figure the upper diagram shows the distribution over the brain of internal carotid, vertebral and maxillary blood in the intact live animal (see key); the lower diagram shows the anatomy which accounts for this distribution, based on the four potential arterial channels to the cerebral arterial circle. Arrows show the direction of flow in the basilar artery. The vertebral–occipital anastomosis (VO) can be disregarded in the intact animal. 1 = internal carotid artery; 2 = basilar artery; 3 = anastomosing ramus from maxillary artery to internal carotid artery; and 4 = connection of vertebral artery to internal carotid artery. **(a)** Dog, man and many other species. 1 (internal carotid artery) and 2 (basilar artery) supply the arterial circle; the basilar artery carries blood to the arterial circle. Neither channel has a rete mirabile. Internal carotid blood reaches all of the cerebral hemisphere except its most caudal part. Vertebral blood supplies the remainder of the cerebral hemisphere, and all the rest of the brain. **(b)** Sheep and cat. Only 3 (maxillary anastomosing ramus) supplies the arterial circle. It has a rete mirabile. 2 (basilar artery) carries blood away from the arterial circle. Maxillary blood is distributed to all of the brain except the caudal part of the medulla oblongata, which is supplied by vertebral blood. **(c)** Ox. 3 (anastomosing ramus) and 4 (vertebral artery) both supply the arterial circle. Each has a rete mirabile. 2 (basilar artery) carries blood away from the arterial circle. A mixture of maxillary and vertebral blood reaches all parts of the brain.

1.3.2 Sheep and Cat

In the sheep and cat species the lumen of the proximal two-thirds of the internal carotid artery becomes obliterated in the weeks or months after birth. (At birth, however, the internal carotid is fully functional.) The **whole** of the adult brain is supplied by maxillary blood via the anastomosing ramus of the maxillary artery (Figure 1.3(b)). A **rete mirabile** (see Section 1.6) develops on the anastomosing ramus in these species. The direction of flow in the basilar artery is **caudal**. Consequently, scarcely any blood from the vertebral artery reaches the brain.

The pressure gradients actually do allow a rostral flow in the **caudal** end of the basilar artery. As a result, vertebral blood does reach the **caudal half** of the medulla oblongata (Figure 1.3(b)). It is certain, however, that **no** vertebral blood reaches the cerebral hemispheres.

1.3.3 Ox

In the ox, the lumen of the **proximal** two-thirds of the internal carotid artery is obliterated by 18 months of age, but the **distal** third remains intact (Figure 1.3(c)). The supply to the **whole** of the brain is by a **mixture** of maxillary and vertebral blood (Figure 1.3(c)). This takes place via the anastomosing ramus of the maxillary artery and the vertebral artery, both of which connect directly to the distal third of the internal carotid artery. A **rete mirabile** develops on both of these channels (see Section 1.6). The direction of flow in the basilar artery is again **caudal** but, as just stated, vertebral blood already gains access to the brain through the distal remnant of the internal carotid artery.

1.3.4 Summary of Species Variations

An inverse relationship exists between the degree of development of the internal carotid and that of the anastomosing ramus of the maxillary artery: when one is large the other is small. In no species are both of these channels fully developed.

In all species, a vertebral–occipital anastomosis (Figure 1.2) is present and well developed. Despite the fairly substantial calibre of this pathway, it seems to have very little functional importance in the intact animal. It does become of interest, however, if the common carotid artery is cut.

1.4 Summary of the Significance of the Vertebral Artery as a Source of Blood to the Brain

In the normal sheep and cat, little or no blood from the vertebral artery reaches the brain. In the normal ox, vertebral blood reaches **all** parts of the brain, and it is this point that becomes particularly important in the matter of humane slaughter (see below). In other species vertebral blood reaches only the cerebellum and the caudal part of the cerebrum.

1.5 Humane Slaughter

The essential characteristic of the Jewish and Mohammedan methods of slaughter is that they consist of a single rapid cut of the neck with an extremely sharp knife, severing among other things the common carotid arteries and the jugular veins on both sides of the neck, but not the vertebral arteries which are protected by the bony walls of the transverse foramina of the cranial six cervical vertebrae. Attempts have been made to apply anatomical and physiological knowledge to determine whether cattle and sheep slaughtered in this way do in fact lose consciousness with sufficient speed to be spared unnecessary suffering. The interpretation of the physiological evidence is controversial, but it appears to indicate that consciousness may be lost between 3 and 10 seconds after the neck is cut; the direct arterial pathway to the cerebral cortex via the vertebral artery in the ox but not in the sheep, suggests that the time taken in the ox may be relatively long (towards 10 seconds), although in the sheep it may be at the lower end of the range (towards 3 seconds). The captive bolt and electrical stunning used in other methods of slaughter are held to disrupt brain function completely within a fraction of one second, if properly used.

In Great Britain, the Slaughter of Animals Act 1958 lays down three conditions for the slaughter of horses, cattle, sheep, pigs and goats in abattoirs: all animals must be either:

1) instantaneously slaughtered by a mechanically operated instrument;
2) stunned mechanically or electrically so as to be instantly insensible to pain until dead; or
3) slaughtered by other means specified by the Minister, provided again that the animals are rendered insensible to pain until death supervenes.

The Jewish and Mohammedan methods of slaughter are exempted from items **1)** and **2)**, but there is an overall proviso that they must not inflict unnecessary suffering.

In the preceding sections, it has been shown how the brain is supplied with blood, and the events which follow the cutting of the neck can now be considered. Immediately after the common carotid arteries have been cut, blood will flow from both their cardiac and their cranial stumps. The blood which escapes from the cut cranial stumps will come from the vertebral arteries, via the occipito–vertebral anastomoses into the common carotid arteries. In the ox, the vertebral arteries could continue to supply the brain via channel 4 (Figure 1.3(c)). However, since the pressure should fall markedly at the cut cranial ends of the common carotid arteries, it is to be expected that most of the vertebral blood will flow down the steeper pressure gradient from the vertebral arteries to the open cranial stumps of the common carotid arteries, i.e. most of the blood from the vertebral arteries should escape from the cut cranial stumps of the common carotid arteries. In the sheep there is no channel 4 (Figure 1.3(b)), so there is less opportunity for blood from the vertebral arteries to reach the brain. But even in the sheep, blood could reach the cerebral arterial circle via the occipito–vertebral anastomoses and channel 3, or by the reversal of flow in channel 2, though once again most of the flow should follow the steep pressure gradient to the cut cranial stumps of the common carotid arteries. One further factor is the possibility that the elastic fibres in the wall of the common carotid arteries may cause rapid retraction of the arterial wall with resultant sealing of the cut stumps. If this were to happen to the cranial stumps of the carotid arteries, the vertebral artery would then supply a closed system of arterial vessels including those to the brain.

Attempts have been made to measure the time taken for the animal to lose consciousness. It has been found that in standing sheep the electroencephalogram begins to change very quickly (about 2 seconds) after cutting the common carotid arteries. In sheep and goats, the corneal reflex is lost on average in about 3 seconds. In cattle, the EEG becomes sleep-like in 3 to 5 seconds, and standing cattle fall within 8 to 10 seconds.

1.6 Rete Mirabile

A maxillary rete mirabile (rete mirabile means 'marvellous network') occurs on the anastomosing ramus of the maxillary artery in all species in which the supply from the maxillary artery is well developed. Thus it occurs in the cat, and in the ox and sheep. In the ruminants (but not the cat) it is immersed in the **cavernous sinus** (see Section 3.7). The last part of the internal carotid artery passes through the cavernous sinus.

The function of the rete mirabile has long been debated. It was thought that it might eliminate pulsation before the blood reaches the brain itself. However, more recent observations indicate that the rete is involved in thermoregulation. The blood in the cavernous sinus comes partly from the nasal mucosa, where evaporative cooling occurs; consequently the blood in the cavernous sinus is cooler than the arterial blood coming direct from the hot core of the body. Presumably heat exchange occurs between the rete blood and cavernous blood, so that rete blood is somewhat cooled before it reaches the brain.

In the sheep, differences of about 1 °C have been recorded between the body core and blood in the hypothalamus. It has been suggested that the object of this temperature difference is to protect the brain against rising temperatures. A notable example occurs in certain gazelles, which possess an intracranial rete mirabile. These animals can tolerate a body temperature of 46.5 °C for long periods; when the body temperature is driven up to 46.5 °C by exercise, the temperature of the brain still remains about 2.9 °C lower than the body core, this lower temperature probably being due to heat exchange between the rete blood and the cavernous blood.

The rete mirabile arises developmentally (Figure 1.4(a), (b)) from many nutrient arterial twigs which form:

1) from the terminal part of the internal carotid near the cerebral arterial circle; and
2) from the maxillary artery, and supply the root of the trigeminal nerve. These nutrient twigs to the Vth nerve are present in mammals generally.

In the few species in which the proximal part of the internal carotid becomes obliterated (sheep, ox, cat) these twigs proliferate, and those from the distal remnant of the internal carotid anastomose with those from the maxillary artery. These anastomoses then form a continuous arterial pathway from the maxillary artery to the cerebral arterial circle, complete with a basket-like plexus, the rete mirabile.

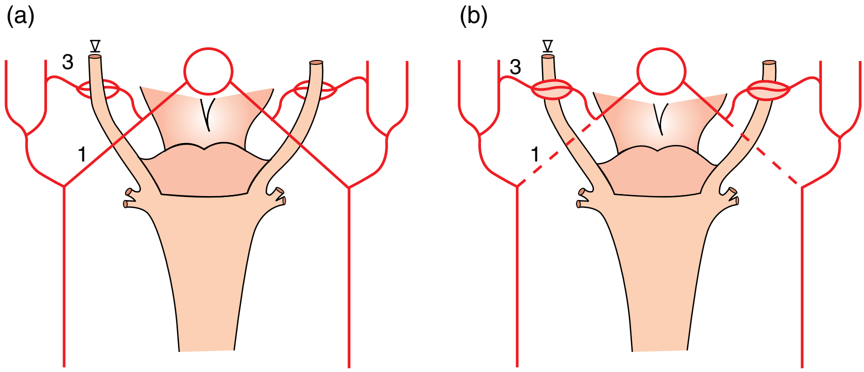

Figure 1.4 **(a), (b)** Diagram showing the probable evolution of the rete mirabile. The trigeminal nerve (V) receives small nutrient branches from the internal carotid artery 1) and maxillary artery 3), in mammals generally (a). When the internal carotid is obliterated in ruminants and the cat, these nutrient vessels anastomose across the trigeminal nerve and so form the rete mirabile (b).

Superficial Arteries of the Spinal Cord

1.7 Main Trunks

Although species variations occur, the basic pattern in mammals is founded on three longitudinal trunks (Figure 1.5).

1.7.1 Dorsolateral Arteries

A pair of small dorsolateral arteries runs along the dorsolateral aspect of the spinal cord. These arteries are ill-defined and in some mammalian species, including the dog, cannot be identified as distinct vessels.

In man, there tend to be two of these arteries on each side, one dorsal and one ventral to the dorsal roots of the spinal nerves.

1.7.2 Ventral Spinal Artery

A much larger and more important midline ventral spinal artery lies in the ventral fissure of the spinal cord.

1.8 Anastomosing Arteries

A sparse and very irregular network of arteries connects the dorsolateral and ventral spinal arteries. However, these anastomoses are inadequate as an alternative pathway. If the ventral spinal artery is blocked, the spinal cord will nearly always be damaged.

At the level of each intervertebral foramen, the anastomosing network tends to be reinforced by an irregular and somewhat incomplete **arterial ring** surrounding the cord (Figures 1.5 and 1.6). This ring receives the incoming dorsal root and ventral root arteries.

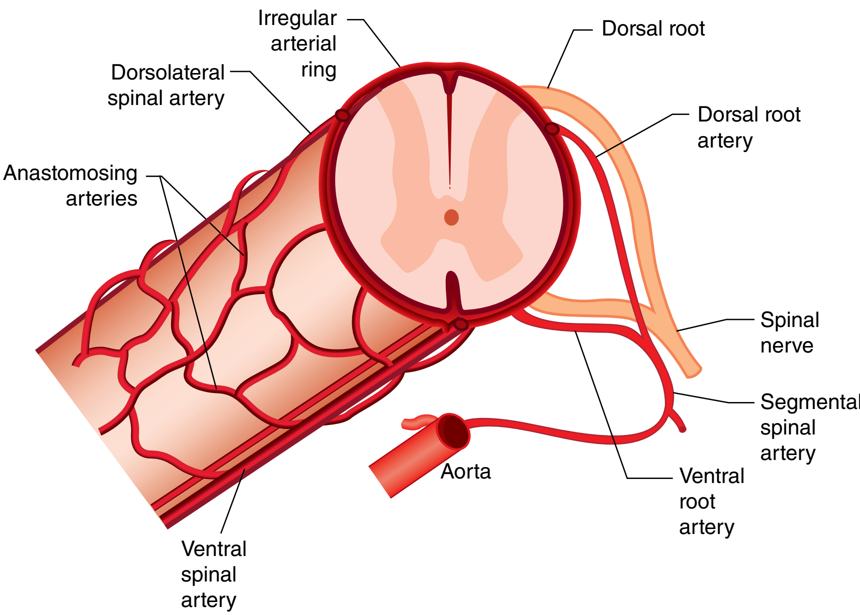

Figure 1.5 Diagram of the superficial arteries of the spinal cord in a hypothetical mammal. Only the ventral spinal artery is constant and relatively large in mammals generally. The paired dorsolateral arteries, the anastomosing arterial network connecting these to the ventral spinal artery, and the arterial ring at the level of each intervertebral foramen, are all inconstant and irregular in disposition depending on the species. These superficial arteries are supplied by paired segmental spinal arteries, which enter the vertebral canal as the dorsal root artery and ventral root artery on each side.

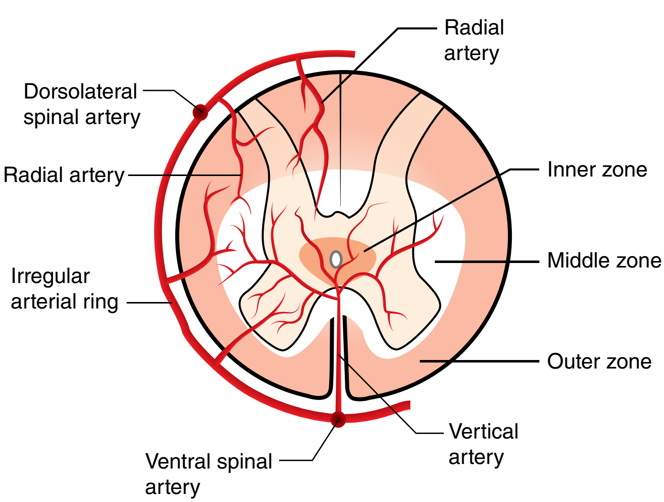

Figure 1.6 Diagram showing the deep arteries of the spinal cord. The inner zone is supplied by vertical arteries only. The middle zone (uncoloured) is supplied by both vertical and radial arteries. The outer zone is supplied by the radial arteries only.

1.9 Segmental Arteries to the Spinal Cord

At each segment of the body, two arteries on the left, and two on the right side, supply the spinal cord. These are the **dorsal root artery** and **ventral root artery** on each side (Figure 1.5). These arteries arise from paired **spinal arteries**, which in turn spring from the paired lumbar arteries of the aorta, from the intercostal arteries, and from the vertebral arteries.

In some species, the dorsal and ventral root arteries are erratically absent from some or many segments of the body.

Besides interrupting the sensory and motor rootlets of that particular segment, injury to the roots of a spinal nerve can interfere with its arteries and thus cause degeneration within the spinal cord itself.

1.9.1 Deep Arteries of the Neuraxis

The general richness of vascularity of the neuraxis (brain and spinal cord) is a notable feature. Although the brain forms only about 2% of the total body weight, it receives about 16% of the total cardiac output, and accounts for about 20% of the total O_2 consumption of the whole body.

1.10 General Principles Governing the Distribution of Arteries below the Surface of the Neuraxis

Axons, cell bodies, and synapses have an increasing requirement for blood and oxygen consumption in that order. Grey matter is therefore more vascular than white.

Motor areas, sensory areas, and associated areas have increasing vascularity in that order. This reflects the functional importance of the association areas of the brain (see Section 18.1).

1.10.1 The Phylogenetic Age of the Region

The ancient parts of the neuraxis typically are less vascular than the recent parts. Thus the spinal cord and the rhinencephalon (the latter being phylogenetically the oldest part of the brain, see Section 9.6) are less vascular than the cerebral cortex and cerebellar cortex. An exception is the hypothalamus which has the richest blood supply in the brain, in spite of being phylogenetically ancient, but this is probably because it depends directly on a high vascularity to carry out some of its functions such as thermoregulation (see Section 17.3).

1.11 The Deep Arteries of the Spinal Cord

Two groups of arteries penetrate the surface of the spinal cord:

1.11.1 Vertical Arteries

A series of vertical arteries arise from the ventral spinal artery like the teeth of a comb and pass, in the ventral fissure, towards the centre of the spinal cord (Figure 1.6). They supply most of the grey matter, and reach peripherally into the white matter also.

In man, each vertical artery passes either to the right or to the left, supplying a territory on either side of the midline.

1.11.2 Radial Arteries

The radial arteries arise from all the other arteries on the surface of the cord. They supply the white matter and the outer regions of the grey matter (Figure 1.6). The spinal cord therefore has three vascular zones (Figure 1.6):

1) The **inner vascular zone** is supplied solely by the vertical arteries of the ventral spinal artery;
2) The **middle vascular zone** is supplied both by the vertical arteries of the ventral spinal artery, and by the radial arteries from all the other surface arteries; and
3) The **outer vascular zone** is supplied by the radial arteries alone.

1.12 The Problem of Pulsation

It appears that large pulsating arteries cannot be tolerated below the surface of the neuraxis. Since the fluid nature of brain tissue renders it incompressible, large pulsating arteries would generate pressure waves below the surface. This may be why no large arteries travel below the surface of the brain and spinal cord.

1.13 Arterial Anastomoses of the Neuraxis

1.13.1 On the Surface of the Neuraxis

Profuse anastomoses occur on the surface of the brain. These can sometimes provide effective alternative channels around an obstruction. The similar anastomoses on the surface of the spinal cord are finer, and generally inadequate as alternative pathways.

1.13.2 Below the Surface of the Neuraxis

The deep arteries rarely anastomose above capillary level. Some workers claim that there are no anastomoses at all above the capillary level; others believe in occasional anastomoses at arteriolar level. Functionally, it matters little, since these arteries below the surface are all **functional end arteries**; thus total obstruction of any artery below the surface produces death of all neurons in its territory within about 8 minutes.

1.13.3 Failure of the Blood Supply to the Neuraxis

The arteries of the brain and spinal cord may be blocked by small blood clots (thrombi) and emboli. Such obstruction results in irrevocable damage.

The arteries which penetrate and supply the depth of the neuraxis are relatively small and tend to arise at right angles from the large parent vessels on the surface. Normally the flow through these small penetrating vessels is already reduced to the minimal effective level; any further lowering of pressure through any local mechanical interference can reduce the flow below critical levels, causing anoxia and damage within the territory of such vessels.

In man, the arteries most often involved in occlusion or haemorrhage ('**stroke**') are a group (the striate arteries) arising from the **middle cerebral artery** and supplying the basal nuclei (basal ganglia) and parts of the internal capsule. Haemorrhage into the brain interferes directly with the function of the territory supplied by the ruptured artery by causing anoxia of the tissues. It also interferes indirectly with the function of adjoining areas by means of pressure from the haemorrhage and oedema. The clinical neurological signs of stroke are surveyed in Section 12.6.

Cardiac arrest during anaesthesia may cause severe damage to the brain, even though the heart beat may be restored so that the subject survives the operation. There tends to be ischaemic necrosis of the cerebral cortex in the territory of the rostral and middle cerebral arteries. The dorsal regions of the cerebral cortex, including the visual area (Figure 9.2(a)), are the most severely affected, and then the lateral regions including the primary motor area. Blindness and extensor rigidity may result.