Cranial Arterial Anatomy

2

Contents

Preamble

The purpose of this tutorial is to outline cranial arterial anatomy for the student endovascular therapist. These details are reproduced widely in text books, so why include them in the tutorials of the Oxford Course? The answer is to give guidance by providing context and suggesting priorities in this core knowledge. The tutorial therefore intends to equip the reader with an understanding of the detail that they need to master in order to practice. Like other tutorials, the attempt is to be both comprehensive and selective. By emphasising areas important to the performance of endovascular treatments, it aims to avoid simply reproducing a standard anatomical text.

The blood supply of the cranium is traditionally described separately as cerebral and craniofacial circulations. The two systems are obviously not isolated from each other, and understanding and recognition of actual and potential connections between them are fundamental practical skills in endovascular neurosurgery. Anastomoses between extra- and intracranial blood supplies are potential dangers and their recognition underpins safe interventions in the head and neck. They will be outlined here but considered again in Tutorial 7. The student needs to realise that if an artery is rarely seen on angiography, it doesn't mean that it is not there or a potential route that may cause a complication during embolisation. Familiarity with small arteries not normally seen on angiography is important for this reason

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because they need to be identified if a disease causes their enlargement. If you don't know where to look, you won't find them.

2.1 Internal Carotid Artery (ICA)

The internal carotid artery originates in the neck as a terminal branch of the common carotid artery (CCA) at the level of the thyroid cartilage, i.e. C3 or C4 vertebrae (but varying between extremes at D1 and C1). It terminates intracranially at the inferior surface of the brain by dividing into anterior and middle cerebral arteries.

No single system for identifying different sections of the large cerebral arteries has been generally adopted. This is particularly the case for the ICA. Fischer in 1938 [4] used a simple code (A1, A2, M1, M2, P1, P3, etc.) to describe sequential arterial sections in the direction of blood flow at and above the circle of Willis[1] based on branch points. This is intuitive and is generally consistently applied in the literature. However, for ICA he used five sections (C1–C5) but applied them in reverse (i.e. from distal to proximal and against the direction of blood flow). Subsequent authors misinterpreted or ignored this convention, and there is now confusion in the literature over the naming of sections of the ICA. So, simple anatomical descriptors will be used for this artery and Fischer's convention for the arteries comprising the circle of Willis. Thus, the ICA will be discussed in four sections: cervical, petrous, cavernous and supraclinoid portions from proximal to distal.

2.1.1 The ICA Cervical Portion

This extends from the bifurcation of the CCA to the skull base. In this section, the artery lies in the carotid sheath with the internal jugular vein laterally and the vagus cranial nerve (tenth) and the cranial root of the accessory nerve (eleventh) that travel with the tenth, lying posteriorly and between these vessels. The sheath, which is comprised of all three layers of the deep cervical fascia, also contains lymph nodes and sympathetic postganglionic fibres from the superior cervical ganglion.

The internal diameter is about 4–5 mm throughout, except at the carotid sinus (often called the carotid bulb by angiographers) where the artery is 7.5 mm wide for a distance of 15–25 mm. The wall of the carotid sinus contains baroreceptors to monitor systemic blood pressure and the carotid body. The carotid body houses chemoreceptor cells that monitor blood oxygen, CO_2 and pH levels and stimulate respiration and heart rate in response to detected hypoxia. These receptors are connected via nerve fibres of Xth and XIth cranial nerves to the cardiovascular centre in the medulla oblongata and nerve endings in the carotid sinus connected to the inferior ganglion of the vagus. The parasympathetic nervous system modulates systemic blood pressure, and endovascular stimulation of the sinus may simulate its physiological response to increases in pressure by signalling to reduce heart rate and, by inhibiting the vasoconstrictor centre of the medulla oblongata, causing peripheral vasodilatation.

The ICA normally (in 80% of individuals) lies initially behind and lateral to the external carotid artery (ECA) but as these arteries run cranially, the ECA inclines superficially to lie lateral to the ICA on a frontal angiogram. With the exception of anatomical variants, no named branches arise from the cervical portion of the ICA. The most common variant is that the ascending pharyngeal artery (APA) arises from the proximal ICA. Other ECA branches may arise from the ICA and agenesis or hypoplasia may occur, as discussed in Tutorial 1.

2.1.2 The ICA Petrous Portion

During its intrapetrous course, the ICA is initially situated within the bony carotid canal before entering the cartilaginous foramen lacerum. It makes a right angle turn in the canal after an initial short vertical section and then runs anteromedially in the horizontal plane where the bony

[1] Thomas Wills (1621–1675) English physician who worked most of his life in Oxford. He described the basal anastomotic ring in 'Cerebri anatome cui accesit nervorum descriptio et usus' published in 1664.

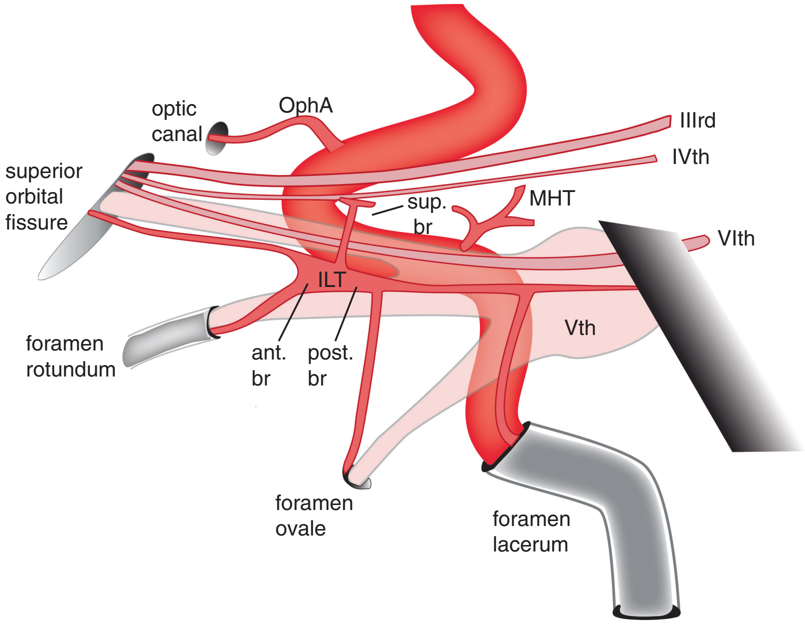

Fig. 2.1 Inferolateral trunk. Diagram showing the three branches of the inferolateral trunk. *ILT* inferolateral trunk, *OphA* ophthalmic artery, *MHT* meningohypophyseal trunk (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

canal is continuous with the foramen lacerum. Its anatomical limit is the petroclinoid ligament where it turns upwards into the cavernous sinus. Sympathetic postganglionic fibres continue into the carotid canal with the ICA where in the horizontal section it is accompanied by a venous plexus. The sympathetic plexus, derived from the superior cervical ganglion, is vulnerable in cases of arterial wall dissection, and its damage causes ipsilateral Horner's syndrome. It leaves the artery in the horizontal section to join the Vidian[2] nerve (with the greater superficial petrosal nerve) in the pterygoid canal and runs anteromedially to the pterygopalatine fossa.

Branches: From the horizontal segment of the petrous ICA arise the caroticotympanic artery and the mandibulo-Vidian trunk (MVT). The former gives the tympanic artery to supply the middle ear. The MVT arises from the ICA in the foramen lacerum. It gives the artery of the pterygoid canal (or Vidian artery) which supplies the sphenoid sinus and anastomoses with the Vidian artery arising from the proximal portion of the internal maxillary artery (IMA) and the mandibular artery. The mandibular artery takes part in the anastomoses around the Eustachian[3] tube.

2.1.3 The ICA Cavernous Portion

Following its petrous passage, the ICA enters the cavernous sinus and lies medial to the Gasserian ganglion, the ophthalmic division of the trigeminal nerve (Vth) and the oculomotor (IIIrd), trochlear (IVth) and abducens (VIth) cranial nerves. It runs horizontally forwards and then turns superiorly and medial to the anterior clinoid process, passing through the dural ring to its final intradural course (Fig. 2.1). The branches that arise in this portion of the ICA are small and difficult to identify individually on angiography but nevertheless as important to the endovascular therapist as to a pituitary surgeon.

2.1.3.1 Branches of the Cavernous ICA

These will be described in three groups.

Group 1: The meningohypophyseal trunk (MHT)

[2] Vidus Vidius (1509–1569) Italian surgeon and anatomist who worked in Florence and Paris and taught at the University of Pisa.

[3] Bartolomeo Eustachi (1514–1574) Italian anatomist whose anatomical drawings were published posthumously because he feared excommunication from the Catholic Church.

The MHT and posterior inferior hypophyseal artery are remnants of the first branchial arch artery and arise from the proximal section of the cavernous ICA (Fig. 1.14). These small vessels may arise from a common trunk or separately as three arteries:

(a) Marginal tentorial and basal tentorial arteries. These dural arteries usually arise as a common trunk (called the dorsal meningeal artery). The marginal (or medial) tentorial artery is memorable because of its wonderfully musical eponymous label as the artery of Bernasconi and Cassinari [1]. It follows the free edge of the tentorium posteriorly and therefore runs medial to the basal artery. The basal tentorial artery runs laterally and divides over the tentorium posterior to its attachment to the petrous ridge. It anastomoses with the posterior branch of the middle meningeal artery (MMA).
(b) Lateral clival artery. This vessel supplies the dura of the clivus dividing into lateral and inferolateral branches, which follow the superior and inferior petrosal sinuses, respectively. They anastomose with the contralateral artery, with dural branches of the MMA and jugular branch of the (APA).
(c) Posterior inferior hypophyseal artery (PIHA). The PIHA supplies the posterior lobe of the pituitary and anastomoses with the capsular arteries of McConnell as well as its contralateral counterpart. It gives a medial clival branch (also, in my view confusingly, called the dorsal meningeal artery by some authors) which anastomosis with the clival meningeal branches of the hypoglossal artery (another APA branch).

Group 2: The inferolateral trunk (ILT)

The ILT was known as the inferior cavernous sinus artery, until renamed by Wickborn and Stattin in 1958 [2] after they identified it on angiograms performed to investigate a meningioma.

It arises on the lateral side of the midsection of the cavernous ICA and crosses over the VIth cranial nerve to divide into three principal branches (Fig. 2.1). These are:

(a) A superior branch which returns medially towards the roof of the cavernous sinus, which it supplies together with the IIIrd and IVth cranial nerves as they lie in the wall of the sinus.
(b) An anterior branch which runs forwards in the cavernous sinus and supplies the IIIrd, IVth and VIth cranial nerves. It gives branches, which traverse the foramen rotundum and the superior ophthalmic fissure to anastomose, respectively, with the artery of the foramen rotundum (a branch of the internal maxillary artery (IMA)) and the deep recurrent ophthalmic artery (i.e. the remnant of the embryonic dorsal ophthalmic artery). A further branch to the foramen ovale anastomoses with the accessory meningeal artery, which, if the ILT is small, may become the dominant vessel supplying its territory.
(c) A posterior branch which follows the VIth nerve posteriorly, which it supplies as well as the maxillary division of the trigeminal nerve and the Gasserian ganglion. It gives dural branches which anastomoses with the marginal tentorial artery and with the MMA laterally in the middle cranial fossa and the recurrent artery of the foramen lacerum. The recurrent artery of foramen lacerum is a small artery, which returns along the carotid canal to the foramen lacerum.

It is usually a branch of ILT that may arise from the MHT. Its importance is because of a potential anastomosis with the superior pharyngeal branch of the APA in the foramen lacerum.

Group 3: The capsular arteries of McConnell

These are a series of small arteries providing a systemic (rather than portal) supply to the anterior lobe of the pituitary and the sella dura. They are of little relevance to the endovascular therapist though they have been implicated in the formation of the uncommon medially directed aneurysm of the cavernous ICA.

If the ILT is absent, the MHT will supply most of its territory, and if a persistent trigeminal artery is present, its carotid connection is at the level of the MHT.

2.1.4 The ICA Intradural Portion

The supraclinoid portion of the ICA is intradural, the artery having entered the subarachnoid space through the dural ring medial to the anterior clinoid process. It turns posteriorly and runs lateral to the optic nerve to terminate by dividing into the anterior and middle cerebral arteries. From this portion arise successively the ophthalmic artery (OphA), the superior hypophyseal artery or arteries, the posterior communicating artery (PComA) and the anterior choroidal artery (AchA). The level of the OphA origin varies, and it may arise in an 'extradural' location below the ring, but this distinction is usually impossible to make from a standard catheter angiogram (DSA) but may be possible on rotational 3D images.

2.1.4.1 Branches

1. Ophthalmic artery (OphA) (Fig. 2.2)

The OphA originates from the anterior surface of ICA and runs forwards into the orbit through the optic canal. In the canal, it is initially lateral

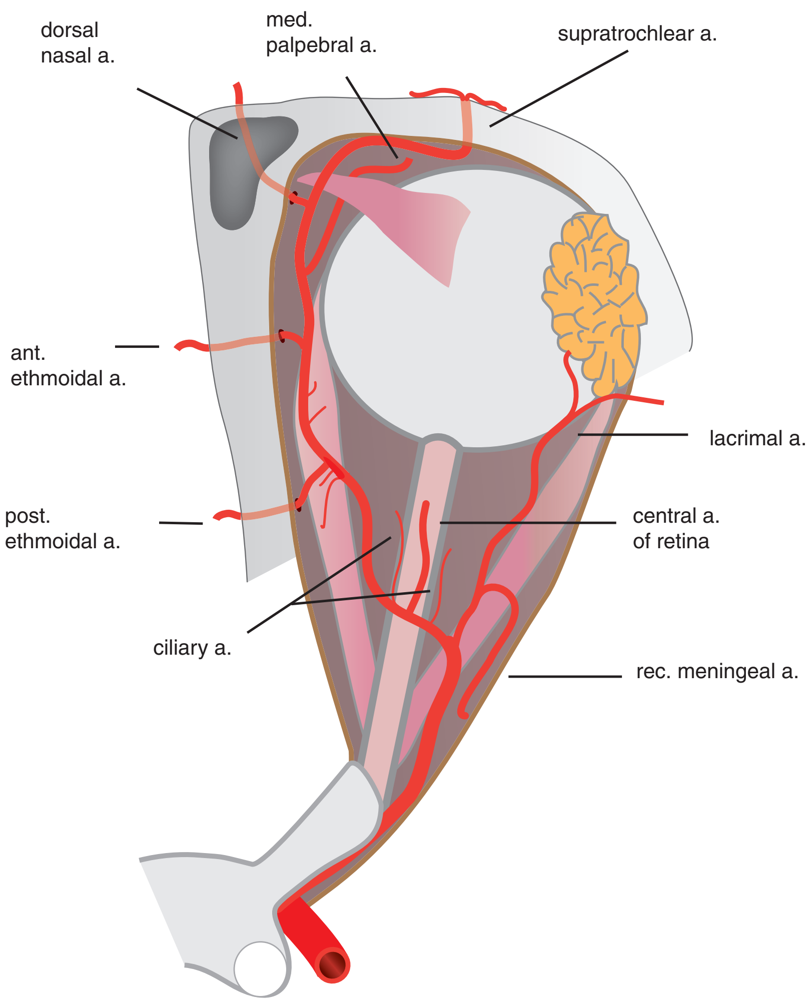

Fig. 2.2 Arteries of the orbit. Superior view of the ophthalmic artery crossing over the optic nerve and running above the medial rectus muscle (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

and then above the optic nerve. Once in the orbit, it runs medially along the upper border of the medial rectus muscle and terminates by dividing into the dorsal nasal artery (or dorsal artery of the nose) and supratrochlear artery. Its major branches are the central artery of the retina (which arises within the optic canal and penetrates the dural sheath of the optic nerve to supply the retina), ciliary arteries (responsible for the choroidal blush), the lacrimal artery (which gives the recurrent meningeal artery and distributes to the lacrimal gland, lateral extraocular muscles and lateral eyelids), the posterior and anterior ethmoidal arteries, the supratrochlear artery and the dorsal nasal artery. The supratrochlear artery runs forwards to the supraorbital notch and is distributed as the supraorbital artery to the skin of the forehead, whilst the dorsal nasal artery supplies superficial structures of the medial orbit and upper nose. The anterior ethmoidal artery gives off anterior meningeal branches (as the anterior artery of the falx) and supplies the mucosa of the superior nasal septum. The posterior ethmoidal artery supplies the posterior ethmoid sinus and part of the posterosuperior aspect of the nasal mucosa. The proximity of the territories of these branches and those of the IMA (in particular the sphenopalatine artery and MMA) makes the study of the vascular anatomy of this region so important (see Tutorial 7). Other small arteries are distributed to the extraocular and palpebrae muscles.

2. Superior hypophyseal artery

The superior hypophyseal artery is infrequently identified on angiograms since it is small and may arise as a single branch or as several small branches. It supplies the pituitary gland and part of the optic chiasm and intracranial optic nerve.

3. Posterior communicating artery (PComA)

The PComA is an anastomotic artery with the vertebrobasilar network and part of the circle of Willis. It joins the posterior cerebral artery between the P1 and P2 segments of that artery. It runs posteromedially above the oculomotor cranial nerve to reach the posterior cerebral artery (PCA).

It gives small perforator arteries from its superior surface that supply the pituitary stalk, optic tract, chiasm and the floor of the third ventricle. A group of small arteries supplying the thalamus and hypothalamus and internal capsule are called the anterior thalamoperforating arteries, but most branches arise from its anterior portion and run medially between the mammillary body and tuber cinereum. Perforating arteries, which share the territory of branches of either PComA or the anterior choroidal artery, may arise from the ICA between the two vessels.

4. Anterior choroidal artery (AchA) (Figs. 2.3 and 2.4)

The AchA arises from the lateral surface of ICA and is applied immediately to the under surface of the brain. It runs posteriorly, passing inferior to the optic tract (from lateral to medial). It then runs around the cerebral peduncle (which it supplies) and recrosses the tract (from medial to lateral) at the level of the lateral geniculate body before passing into the middle part of the choroidal fissure to reach the choroid plexus of the lateral ventricle. Prior to entering the choroid fissure, it gives a series of perforator arteries, which supply the posterior limb of the internal capsule, in particular its inferior level and part of the retrolenticular segment. It gives small branches to the optic radiation, the lateral geniculate body, the angle of the hippocampus and the amygdala as well as part of the globus pallidum and thalamus. The intraventricular terminal branches anastomose with the lateral posterior choroidal artery and follow the choroid plexus from the temporal horn to the trigone area [3]. It may, in addition, supply part of the inferior cortex of the adjacent temporal lobe.

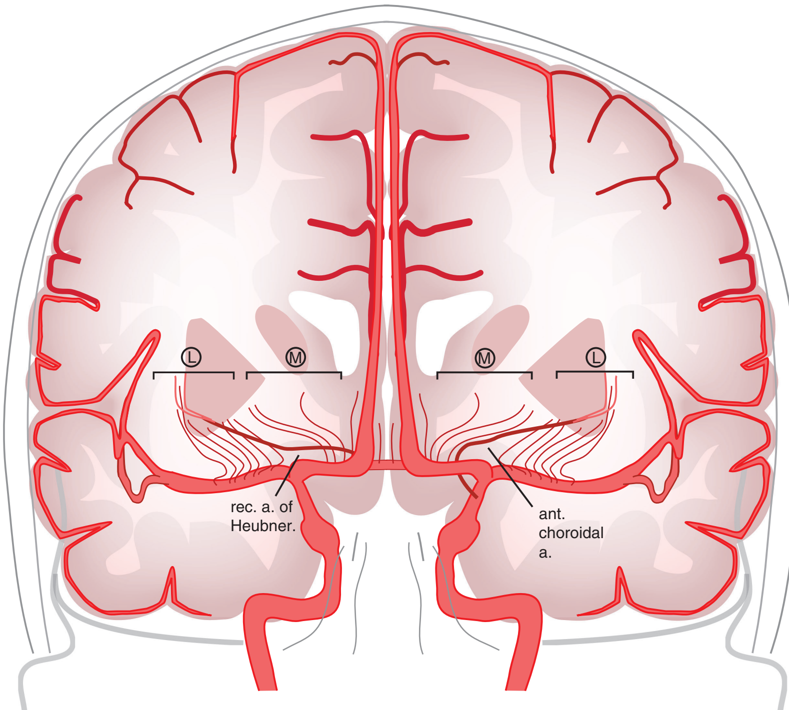

Fig. 2.3 Artist's impression of the anterior circle of Willis showing lenticulostriate arteries arising from the anterior cerebral arteries (*M* medial group) and middle cerebral artery (*L* lateral group). On the left, the anterior choroidal artery (AChA), and on the right, the recurrent artery of Heubner (RaH) is shown (see Fig. 2.4). Note that anterior perforating arteries also arise from the anterior communicating artery (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

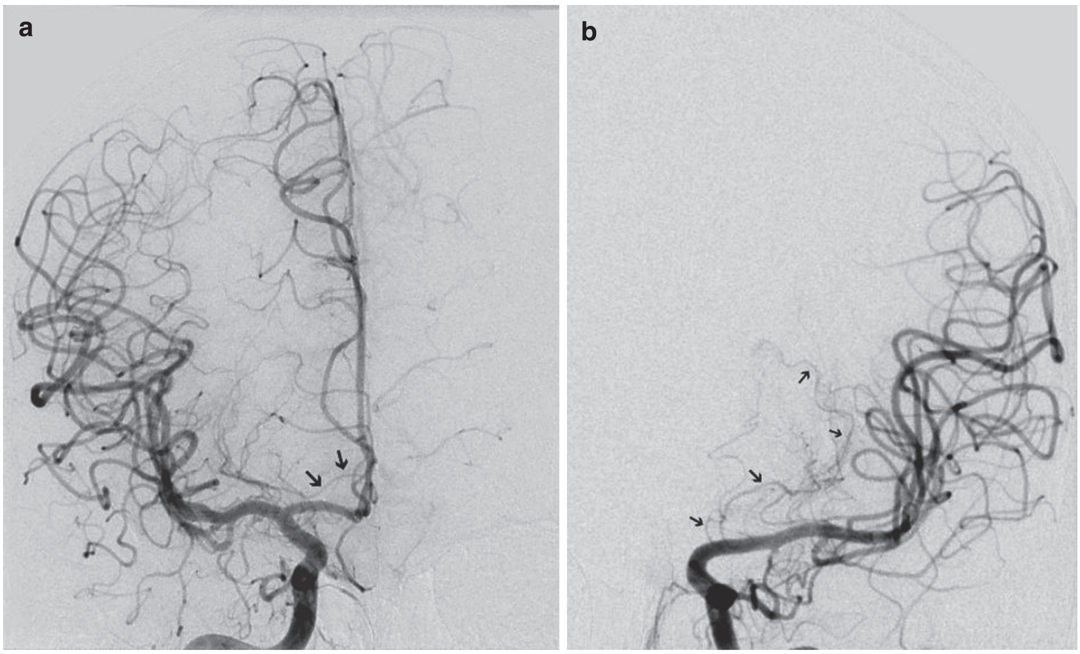

Fig. 2.4 Internal carotid angiograms in the frontal projections. Right (**a**) shows the recurrent artery of Heubner arising from the A2 (*2 arrows*) and left (**b**) with absent anterior cerebral artery shows the anterior choroidal artery (*arrows*)

2.2 The Terminal Branches of the Internal Carotid Artery

2.2.1 Anterior Cerebral Artery (ACA)

The ACA originates below the anterior perforating substance, lateral to the optic chiasm (Fig. 2.3). The convention proposed by Fischer [4] will be used to describe sections of the larger arteries. Thus, the A1 section runs horizontally forwards and medially, crossing above the optic nerve to the anterior inter-hemispheric fissure, where it communicates with its counterpart via the anterior communicating artery (AComA). The ACA then changes direction, and the A2 section runs upwards and forwards in the fissure to reach the genu of the corpus callosum. The definition of the junction of A2 and A3 sections is anatomically difficult because the Fischer convention is based on the numbering of arterial sections up to the next major branch point or bifurcation. In the case of the distal ACA, the next major branch point is the origin of the callosomarginal artery, but its branch pattern is more varied than is usual in the arterial tree. A solution is to define the junction as the point at which the ACA turns to run over the genu of the corpus callosum and so the A3 section starts at the genu and the A4 when the artery reaches the body of the corpus callosum. Confusingly Fischer added an A5 section to designate the artery posterior to the coronal suture (but since we now use bone-subtracted angiograms, this is a less useful landmark). In practice, because of the high level of individual variability, it is sensible to learn an ideal pattern using whatever convention one likes and expects to have to adapt it on a case-by-case basis.

After passing superior to the genu, the A4 section follows the corpus callosum posteriorly either on its surface or in the cingulate sulcus convexity. It terminates as the posterior pericallosal artery passes along the body of the corpus callosum to the splenium for a variable distance which may extend to the region of the pineal body.

2.2.1.1 Branches: A1 Section (Pre-communicating Artery)

1. Lenticulostriate arteries. The medial group of lenticulostriate arteries arise from the A1 section. The majority are short central or diencephalic arteries which arise from the superior surface close to the origin of ACA and run into the anterior perforating substance to supply the anterior basal ganglion and anterior commissure. Medial branches piece the lamina terminals to supply the anterior aspect of the lateral wall of the third ventricle, the anterior hypothalamus and septum pellucidum. Inferiorly directed branches supply the optic nerve and chiasm.
2. Recurrent artery of Heubner. This vessel represents a long central artery which arises either from A1 or A2 sections of ACA (rarely from the AComA) and terminates by supplying part of the head of the caudate nucleus, the anterior portion of the lentiform nucleus and the neighbouring portion of the internal capsule. It usually runs parallel and above the A1 section, directed medially if arising from A1 or laterally if recurrent from an A2 origin. Lateral to the ICA bifurcation, it enters the anterior perforating substance (Fig. 2.4).
3. Anterior communicating artery (AComA). This short anastomotic artery gives perforating arteries, which parallel those of the A1 section to supply the septum pellucidum, corpus callosum and lamina terminalis. It gives posterior directed branches to the chiasm and hypothalamus.

It is estimated that only 30–40% of adults have a single communicating artery, and two or more connections are present in the majority. This is well known to operating neurosurgeons, but multiple channels may be overlooked during diagnostic angiography because they are small and don't always fill because the flow of radiographic contrast media is distorted by blood flow from the contralateral A1. There is a substantial literature describing a plethora of possible variations and asymmetric arterial dispositions which are consequence on the coalescence of the cranial division of the embryonic carotid artery (primitive olfactory artery) in the midline. These variations will not be discussed here, but the student should recognise the possibility of an azygos (i.e. single) A2 vessel (Baptista type 1) and the presence of a third A2 artery arising from the anterior communicating artery following the course of a pericallosal artery. The reader is directed to the works of Rhoton [5] and Baptiste [6] for an idea of the described variation in the communication complex and the distal anterior cerebral arteries.

2.2.1.2 Branches: A2 Section

The A2 section of the ACA thus runs superiorly to the genu of the corpus callosum (Fig. 2.5). The callosomarginal artery may arise from this section but the main branches are:

1. Orbitofrontal artery. This cortical artery runs forwards in the inferior inter-hemispheric fissure and supplies the gyrus rectus, olfactory bulb and the medial inferior frontal lobe.
2. Frontopolar artery. This artery arises at some point below the genu of the corpus callosum to supply frontal cortex. It may arise as more than one vessel.

2.2.1.3 Branches: A3 Section (Distal to the Origin of the Callosomarginal Artery or the Genu)

The ACA distal to the genu of the corpus callosum is called the pericallosal artery, a term that includes the A3 and distal sections. The callosomarginal artery typically arises at the level of the genu of the corpus callosum and runs parallel to the pericallosal artery in the cingulated sulcus. Its size is inversely related to the size of the pericallosal artery and it is frequently larger [7].

The callosomarginal artery gives a group of four branches:

(a) Anterior internal frontal
(b) Middle internal frontal
(c) Posterior internal frontal
(d) Paracentral artery

These divide into a network of sulcal vessels to supply the medial frontal lobe, classically as far as the central sulcus, but the arterial pattern that delivers this supply varies depending on whether the stem artery arises from pericallosal or callosomarginal arteries.

2.2.1.4 Branches: A4 and A5 Sections

In its A4 and A5 final sections, the pericallosal artery runs posteriorly over the body of the corpus callosum in the cistern of that name. It terminates and anastomoses with the posterior pericallosal artery which arises from the PCA.

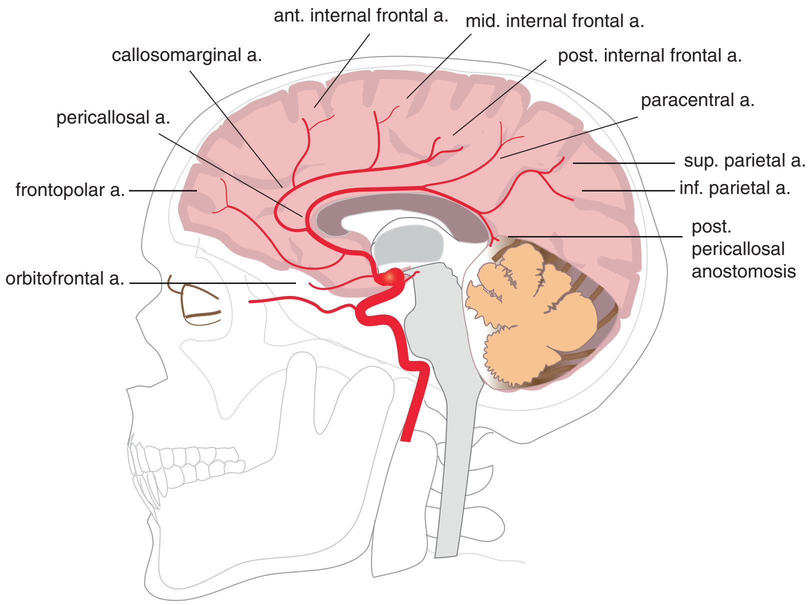

Fig. 2.5 Distal branches of the anterior cerebral artery (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

It gives:

(a) Short callosal perforating arteries that piece the corpus callosum and supply the pillars of the fornix and anterior commissure.
(b) Long callosal arteries that run parallel to the main trunk for a variable distance, supplying the adjacent cortex and may participate in the anastomoses at the splenium.
(c) Dural branches to the adjacent falx.
(d) Parietal arteries. These are the terminal cortical branches to the medial parietal lobe. They may be separable as a superior parietal artery and an inferior parietal artery which arise posterior to the callosomarginal artery and distribute to the cortex via their respective sulci.

Anatomical variants in the ACA pattern are not infrequent and occur in 20% of patients according to various authors. Common variants include absence or hypoplasia of the AComA and asymmetry of the proximal ACAs cerebral arteries with the entire territory supplied from one ICA. In addition to the collateral blood flow to the contralateral hemisphere provided by the AComA, cortical branches of the ACA border the middle cerebral and the posterior cerebral arterial territories. These can provide efficient collateral support in cases of proximal carotid occlusion when the AComA is ineffective or only partially effective or in cases of occlusion of the A2 and more distal ACA.

2.2.2 Middle Cerebral Artery (MCA)

The MCA arises as the lateral terminal branch of the ICA (Fig. 2.6). It runs horizontally and laterally to its primary bifurcation at the limen insulae (M1 segment). The upper and lower trunk arteries thus formed turn upwards and run in the Sylvian fissure lateral to the insular cortex (M2 segment), before they turn laterally in the horizontal portion of the fissure above the temporal and below the frontal lobe opercular surfaces (M3 segment). They emerge from the fissure in a series of branches (M4 segment). These turn inferiorly or superiorly to respectively supply the cortex of the temporal and frontal lobes.

The angular artery is often described as the continuation of the MCA because it lies at the

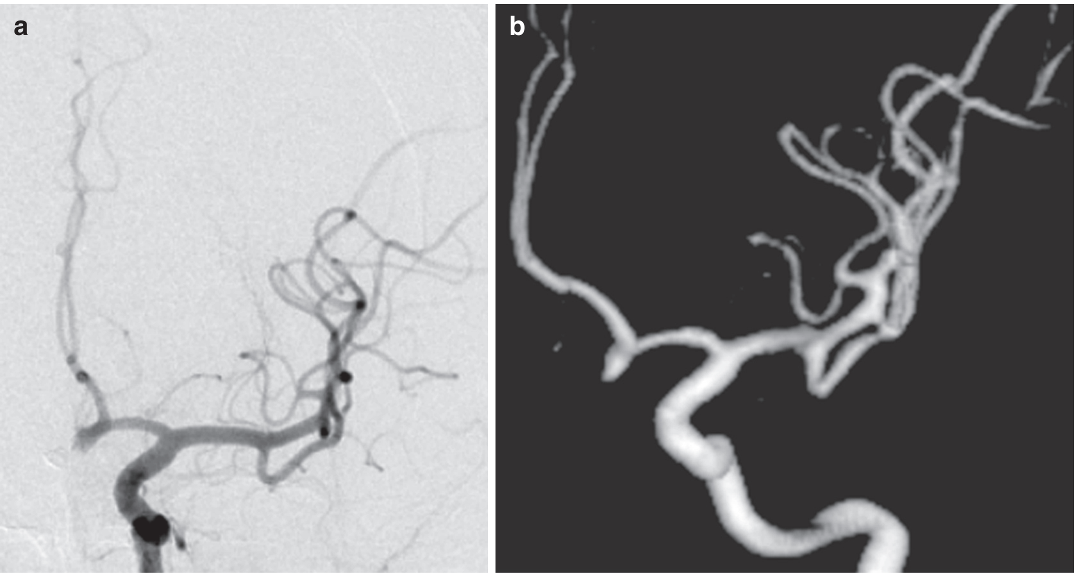

Fig. 2.6 Frontal DSA of the middle cerebral artery bifurcation in a patient with a dominant upper trunk shown in 2D (**a**) and 3D reconstruction (**b**). The upper trunk supplies the anterior (frontal lobe) and the lower trunk the posterior (posterior temporal and parietal lobe, including the central sulcus) portions of the middle cerebral artery territory, though parietal branches may arise from either trunk

centre of this candelabrum of branches when viewed on lateral angiography. It exits from the posterior limit of the Sylvian fissure and is therefore a landmark for mapping the 'Sylvian triangle' of vessels (a useful 'tool' used by pre-CT neuroradiologists to decide if a mass originated in the temporal or frontal lobe).

Descriptions of the configuration of the primary MCA bifurcation vary. It is usually described as a bifurcation with variant trifurcations or 'quadrifications'. What is clear is that the majority of anatomical dissections show a bifurcation. I suggest it is easiest to consider this as the standard and the trifurcation appearance due to early rebranching of one of two primary trunks (i.e. the upper and lower MCA trunks).

The relative positions of the upper and lower trunks can be difficult to distinguish on two-dimensional imaging, but it is important to recognise that the lower trunk branches contribute to the posterior part of the territory (and therefore it is the usual origin of the angular artery). Since the upper trunk supplies the anterior part of the territory (i.e. frontal lobe and a variable amount of the temporal lobe), the presence of a pre-bifurcation (M1) branch directed to the frontal or anterior temporal lobe may result in it being smaller than the lower trunk.

2.2.2.1 Branches

These should be considered as deep (perforator) and superficial (cortical) arteries.

1. Lenticulostriate arteries. These arise from the superior surface of the M1 section. They are grouped as the medial and lateral lenticulostriate arteries which piece the anterior perforating substance to supply the globus pallidum and lentiform nucleus (medial group) and passing through the globus pallidum supply, the superior part of the internal capsule and the upper part of the head and body of the caudate nucleus (lateral group). The territory of the medial group overlaps with those arising from A1.
2. Cortical arteries. The superficial or cortical branches supply a considerable proportion of the superficial hemispheric cortex. They follow the sulci of the brain, and their description (and relative size of each stem artery) depends on the distances between branch points. For those who like to memorise lists, they are shown in Fig. 2.7. However, I prefer to identify only the lobe to which they are directed and their relationship to the Rolandic fissure and the Sylvian point. The last being the site at which the angular artery emerges from the posterior Sylvian fissure.
   (a) Arteries to the temporal lobe. These run inferiorly after leaving the lateral sulcus of the Sylvian fissure and are arranged from anterior to posterior:
      (i) Temporal polar artery
      (ii) Anterior temporal artery
      (iii) Middle temporal artery
      (iv) Posterior temporal artery
   (b) Arteries to the frontal lobe. These run superiorly after leaving the fissure, from anterior to posterior:
      (i) Orbitofrontal artery of the middle cerebral artery
      (ii) Prefrontal artery (supplies Broca's area)
      (iii) Precentral artery (or pre-Rolandic[4] artery of Sillon)
      (iv) Central artery (or artery of the Rolandic fissure)

(c) Arteries to the parietal and occipital lobes. These run posterior to the Sylvian fissure, from superior to inferior:
(i) Anterior parietal
(ii) Posterior parietal
(iii) Angular artery
(iv) Occipitotemporal artery

Cortical arteriolar-arteriolar anastomoses exist between branches of the anterior and posterior cerebral arteries and between the distal branches of the MCA. They are often seen in patients with occlusion of the proximal MCA and become more reliable, as collateral support to the cortex,

[4]Luigi Rolando (1773–1831) Italian anatomist and physiologist who worked in Turin and Sardinia.

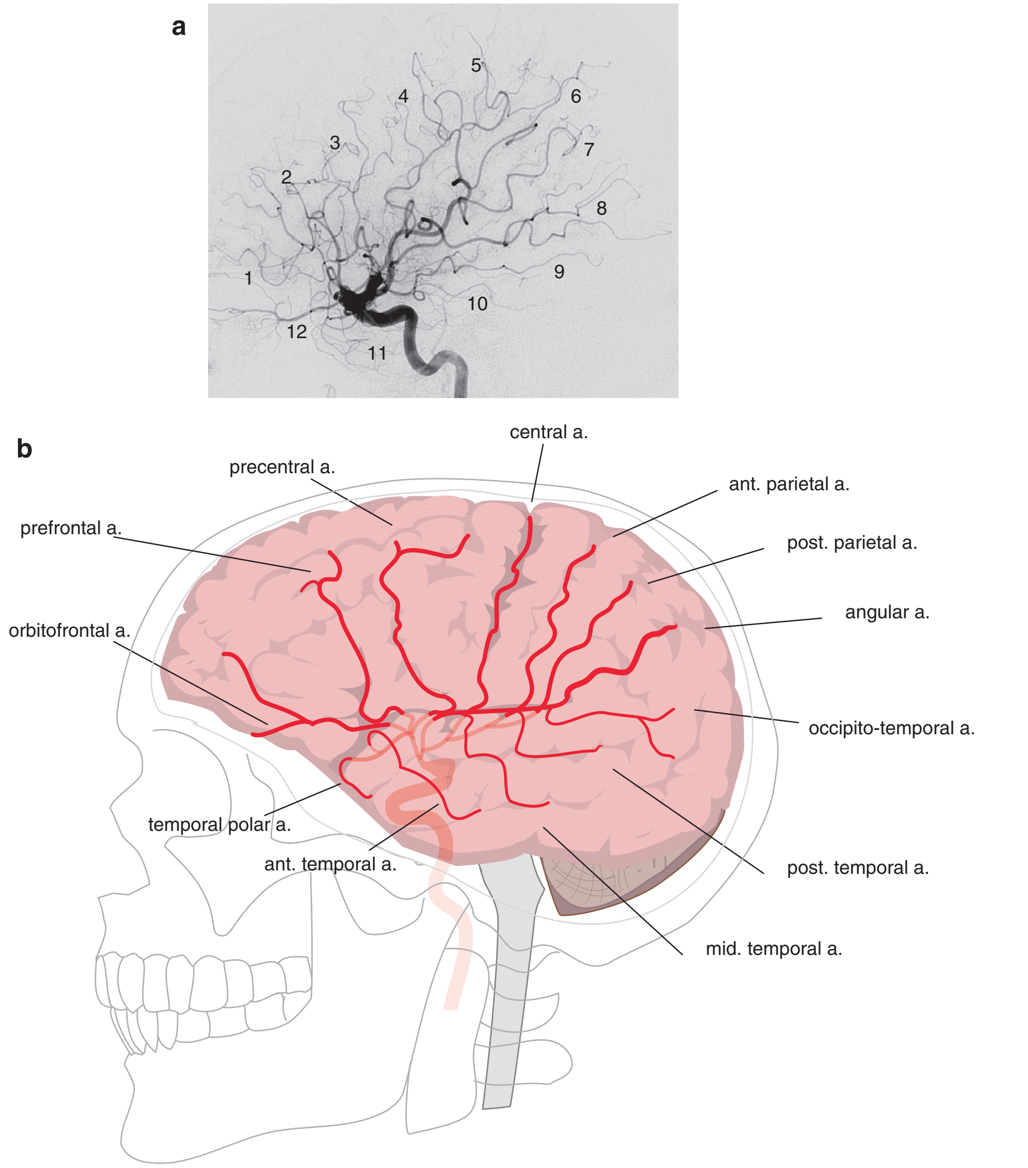

Fig. 2.7 Cortical branches of the MCA, shown on lateral carotid DSA (**a**) and illustrated in (**b**) and in a patient with an absent A1 artery showing the cortical branches of the left MCA. Legends (**a**) Key: *1* orbitofrontal a. *2* prefrontal a. *3* precentral a. *4* central a. *5* ant. parietal a. *6* post. parietal a. *7* angular a. *8* occipito-temporal a. *9* post. temporal a. *10* mid. temporal a. *11* ant. temporal a. *12* temporal polar a (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

if occlusions are made distal to the first branch point (i.e. MCA bifurcation), though there is obviously a limit to how distal embolisation can be tolerated in any tree.

2.3 The Vertebrobasilar System

The vertebrobasilar or posterior cerebral circulation supplies the posterior part of the brain, namely, the occipital lobes, parts of the temporal and parietal lobes, thalamus and cerebral peduncles, the brain stem, cerebellum and the superior portion of the cervical cord. It supplies cranial nerves and contributes to the blood supply of dura and extracerebral structures of the skull base and upper spine. It comprises the vertebral, basilar and posterior cerebral arteries and their branches. It is normally connected to the carotid territory by the posterior communicating arteries.

2.3.1 Vertebral Artery (VA)

The vertebral arteries are paired and have variable calibres of about 3–4 mm with the left usual larger (dominant). They are the first branch of the subclavian arteries that arise from its superior aspect and run vertically and posteriorly to the level of C6 where they enter the foramen in the transverse process. The VA then runs superiorly in the vertebral canal passing through foramina in the transverse processes of all the upper cervical vertebrae. After leaving the superior border of the foramen of the atlas (C2), it runs horizontally and posteriorly to pass through the more laterally positioned foramen of the axis (C1) and then turns medially to the foramen magnum. There, it penetrates the atlanto-occipital membrane and dura to enter the cranial cavity through the foramen magnum and then runs upwards and medially to terminate as the basilar artery, formed by joining its contralateral counterpart anterior to the upper border of the medulla oblongata.

2.3.1.1 Extracranial Branches

In its extracranial course, the VA gives branches, which supply the spinal cord and its dura, cervical vertebrae and muscles, as well as the dura of the inferior posterior fossa (Fig. 2.8). These include (from proximal to distal):

1. Branches to the superior cervical ganglion (stellate ganglion).
2. Spinal arteries: C6–C1. The spinal arteries supply the nerve roots, root sheaths and bone structures of these vertebrae, together with the

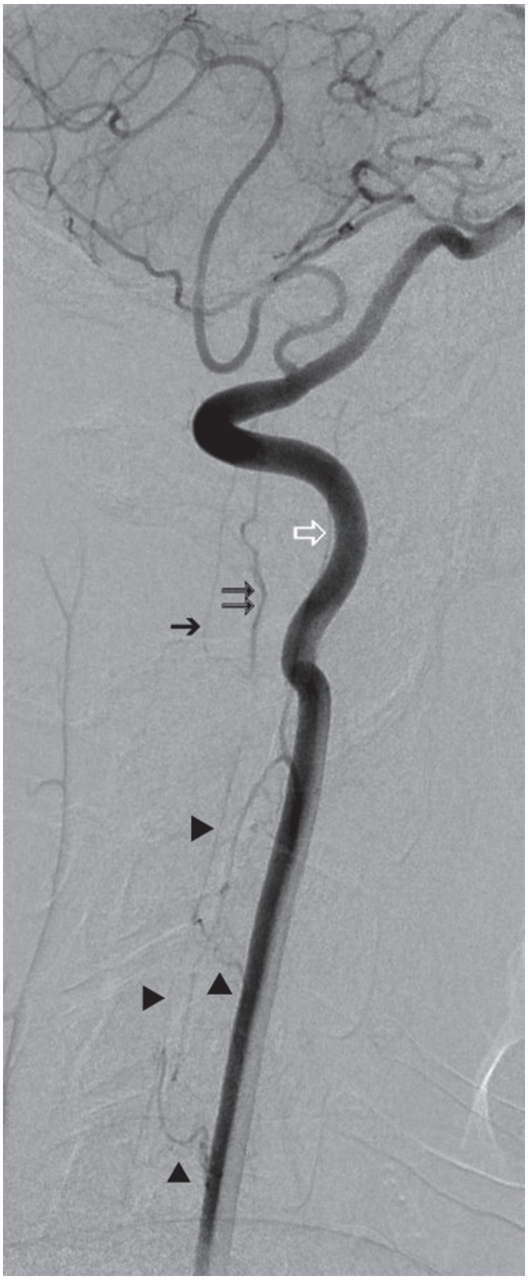

Fig. 2.8 Vertebral artery DSA (lateral view of the *right* side). At C3, a spinal artery branch is seen running cranially to the odontoid arcade (*white arrow*). The anterior spinal artery is seen in the mid-cervical spine with contributing segmental spinal arteries at C4 and C5 (*arrowheads*). The posterior-lateral spinal artery fills in the upper spine (*black arrow*) via a contribution from the lateral spinal artery (*double black arrows*). The lateral spinal artery is a descending branch of the intracranial vertebral artery

deep cervical artery (costocervical trunk) and ascending cervical artery. From C3 to C1 levels, spinal branches of the VA contribute to the odontoid arterial arcade together with collaterals from the ascending pharyngeal artery and occipital artery.

3. Arteries of the cervical expansion. Spinal radiculomedullary arteries support the anterior spinal and posterolateral spinal arteries in the lower cervical spine (i.e. the cervical expansion) and arise between C6 and C4. They are usually bilateral and may arise from the thyrocervical trunk or the ascending or deep cervical arteries.
4. Muscular branches to the paraspinal muscles. These anastomose with branches of the deep cervical and occipital arteries.
5. Anterior meningeal artery. This very small artery arises from the distal VA and supplies the dura of the anterior foramen magnum and the inferior clivus. It also takes part in the anastomoses forming the odontoid arterial arcade (Fig. 2.9).

2.3.1.2 Intracranial Branches

In its intracranial portion, the VA gives branches that supply dura and the upper cervical cord, medulla oblongata and cerebellum. These are:

1. Posterior meningeal artery and artery of the falx cerebelli. The VA may be the dominant source of the artery of the falx cerebelli. This easy-to-recognise vessel may arise from the extracranial VA or from the occipital artery or PICA.
2. Medial group of perforator branches. These supply the medulla oblongata and pyramids. An artery to the foramen caecum is described which is one of this medial group of perforators. It ascends to the pontomedullary junction, where a concentration of perforator arteries congregates in the midline to pass deep into the brain stem, and supplies nuclei of the floor of the fourth ventricle and long tracts.
3. Anterior spinal artery. The rostral origin of the anterior spinal artery is usually bilateral arteries, but one side is often larger. They descend to unite and form a single median artery at the C2/C3 level.
4. Posterolateral spinal arteries. The cranial origins of these paired longitudinal arteries arise from the VA or PICA. They are reinforced by spinal branches of the extracranial VA arteries.
5. Lateral spinal artery. This small branch of VA supplies the IXth cranial nerve and runs caudally supplying the lateral spinal cord to join the ipsilateral posterolateral spinal artery at C4. It may arise from PICA.
6. Posterior inferior cerebellar artery (PICA). The PICA arises 15 mm proximal to the termination of the VA. It is of variable calibre being reciprocal in size to that of the ipsilateral anterior inferior cerebellar artery. Classically, the PICA course is separated into five sections: anterior medullary, lateral medullary, tonsillomedullary, telovelotonsillar and cortical (Fig. 2.10).

The anterior medullary section is intimately related to the hypoglossal nerve (which lies anterior and between PICA and its parent VA). The lateral medullary section runs around the inferior surface of the olive to the XIth cranial nerve. The tonsillomedullary section carries the artery between the spinal and cranial roots of the XIth cranial nerve and then behind the Xth and IXth cranial nerves to the telovelotonsillar section where it runs medial to the cerebellar tonsil. It enters the telovelotonsillar section at the midpoint of the tonsil. Then, it runs medial to the tonsil and lateral to the vermis to reach the cortical surface of the cerebellar hemisphere and its last (cortical) section. This complicated description highlights the difficulty of surgical dissection needed when clipping aneurysms at the PICA origin and reflects its importance (in the past) for determining the position of the cerebellar tonsils relative to the foramen magnum.

It comprises branches:

(a) Perforators to the lateral and posterior aspect of the medullar oblongata from the proximal three sections. These are small branches that supply the lateral medulla and olive. They are sometimes described as circumferential arteries depending on their length.

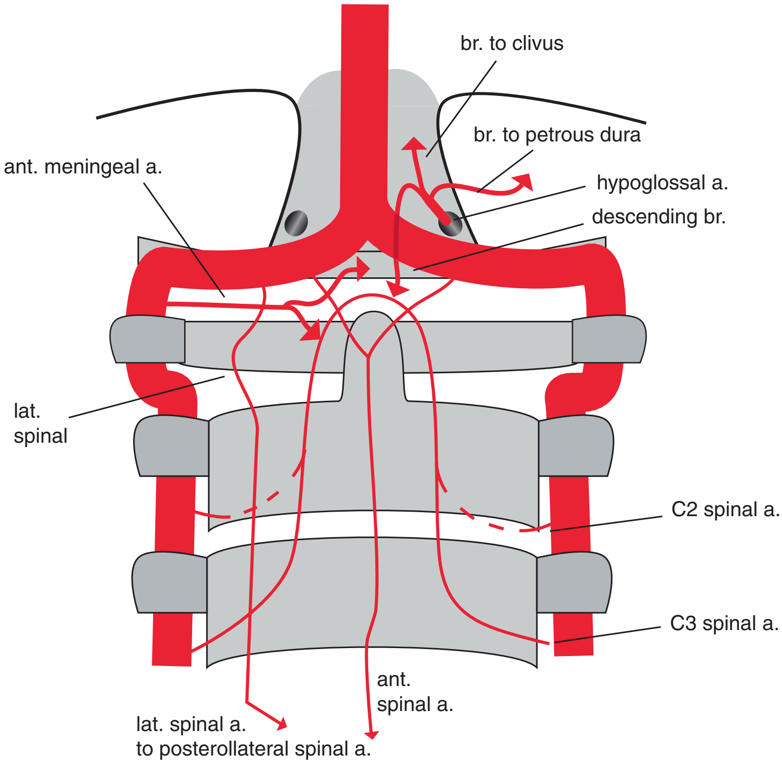

Fig. 2.9 Arteries of the odontoid arcade (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

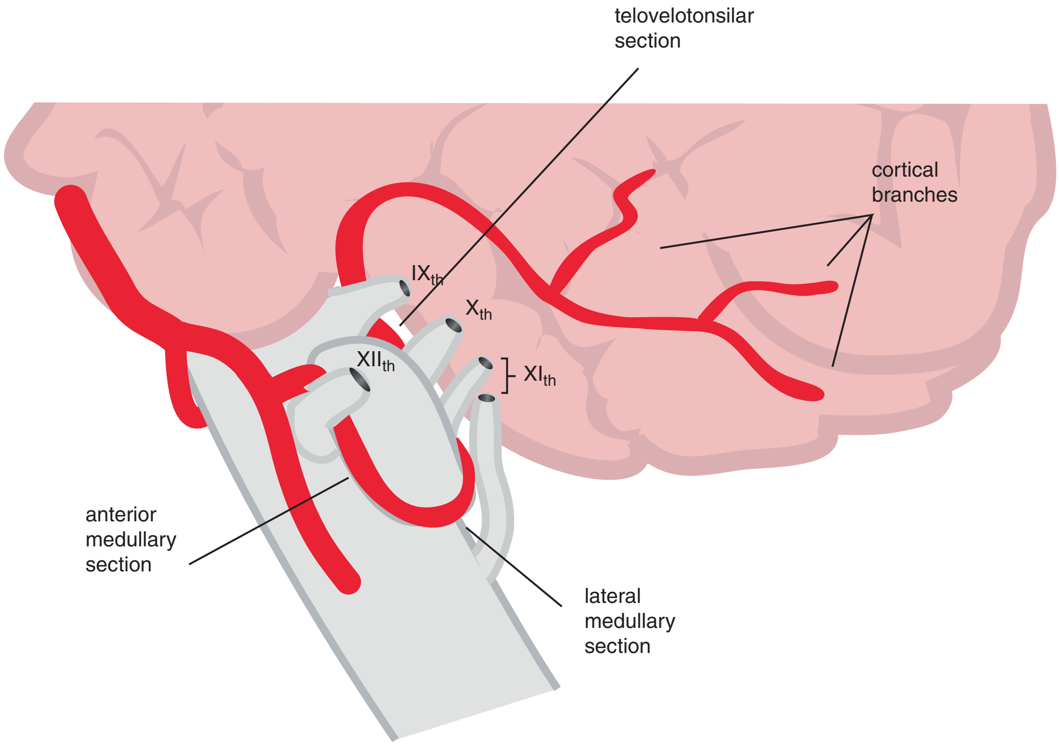

Fig. 2.10 Proximal sections of the posterior inferior cerebellar artery (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

(b) Choroidal arteries. These arise from the tonsillomedullary and telovelotonsillar sections. The apex of the cranial loop (telovelotonsillar sections) is described as the choroidal point, which marks the roof of the fourth ventricle on the lateral angiogram. It is the distal limit for perforator arteries to arise from the PICA trunk.

(c) Terminal cortical branches supply the postero-inferior aspect of the cerebellar hemispheres and a median branch to supply the vermis, the choroid plexus and the fourth ventricle.

(d) The lateral spinal artery and posterior meningeal arteries may arise from the PICA rather than the VA.

2.3.2 Basilar Artery (BA)

The BA arises just below the pontomedullary junction between the emerging VIth cranial nerves and runs superiorly on the anterior surface of the pons to terminate at the pontomesencephalic junction. The level of the basilar bifurcation is variable. It is usually within 1 cm of the superior surface of the dorsum sella, but in 30% of individuals, it is above and in 20% below this range. Relative to the brain stem, the termination can be as far caudal as 1 cm below the pontomesencephalic junction and as far rostral as the mammillary bodies.

2.3.2.1 Branches

Its branches can be divided into two groups: the perforating arteries and the long circumferential arteries. The perforating arteries are paramedian and circumferential in distribution. They supply the corticospinal tracts, other connecting white matter tracts and the vital deep nuclei of the pons and midbrain. In the physiological state, they are rarely visible on angiography and do not cross the midline.

The long circumferential arteries consist of three paired vessels:

1. The internal auditory artery (labyrinthine artery) which arises from the basilar artery or AICA and runs laterally to the internal auditory canal where it gives cochlear and vestibular branches. A small branch, the subarcuate artery, supplies meninges of the subarcuate fossa and the bone of the semicircular canals.
2. The anterior inferior cerebellar artery (AICA) arises at the junction of lower one-third and upper two-third of the basilar artery and runs laterally on the anterolateral surface of the pons to the flocculus. It supplies the inferior cerebellar peduncle, the middle cerebellar peduncle and the inferior portion of the flocculus and the adjacent cerebellar hemisphere. The choroid plexus of the lateral recess of the fourth ventricle is also supplied by this artery. It anastomoses on the surface of the cerebellar hemispheres with branches of PICA and the superior cerebellar arteries.
3. The superior cerebellar artery (SCA) arises 1–3 mm below the termination of BA and parallels the course of the PCA around the cerebral peduncle in the ambient cistern. It is separated from the PCA by the oculomotor nerve cranial nerve medially and the trochlear nerve cranial nerve laterally. Lying below the free edge of the tentorium, it gives the medial dural-tentorial artery [11]. Posterolateral to the midbrain it gives the superior vermian artery and then terminates in cortical branches to the superior cerebellar hemisphere. It supplies the superior cerebellar peduncle and part of the middle cerebellar peduncle, the dentate nucleus, roof of the fourth ventricle, as well as the superior portion of the cerebellar hemispheres.

2.3.3 Posterior Cerebral Artery (PCA)

The paired posterior cerebral arteries are the terminal branches of the basilar artery and complete the posterior circle of Willis (Fig. 2.11). The PCA can be described in three main sections: P1, from the origin to PComA; P2, running around the cerebral peduncle; and P3, posterior to the midbrain to the anterior limit of the calcarine fissure. The main trunk continues posteriorly and terminates by dividing into parieto-occipital and

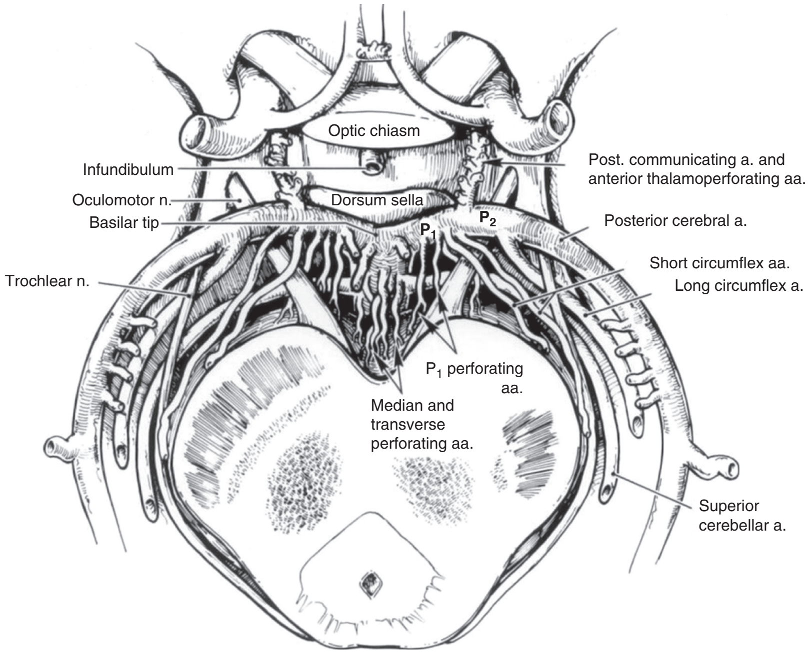

Fig. 2.11 Artists impression of the basilar artery termination and proximal posterior cerebral arteries (Reproduced with permission from Wascher TM, Spetzler RF. Saccular aneurysms of the basilar bifurcation. In: Carter LH, Spetzler RF, editors. Neurovascular neurosurgery. New York: McGraw-Hill; 1994. p. 730)

occipital branches, with the calcarine artery usually arising from the latter.

The P1 section passes around the front of the cerebral peduncle, above the IIIrd and IVth cranial nerves, and receives the PComA at the level of the IIIrd nerve.

The P2 section then runs laterally and posteriorly (parallel to the SCA) to reach the inferior surface of the temporal lobe. It runs in the ambient cistern, whose anterior portion is sometimes called the crural cistern (i.e. the portion extending from the uncus to the cerebral peduncle).

The P3 section continues in the ambient cistern and then in the lateral part of the quadrigeminal cistern. As it runs posteriorly, the PCA turns towards the midline, under the splenium of the corpus callosum.

From this short arterial segment, a large number of small arteries arise which supply mesencephalon and diencephalon structures and the choroid plexus. They are described in anatomical texts as groups of perforators or arterial stems with frequent multiple origins and variations in sites of origin from the PCA parent, but in this plethora of data, it is important for the student to realise that the proximity of their origins and target territories means that overlaps are inevitable. With this in mind, a standard description of the PCA branches follows.

2.3.3.1 Branches: P1 Section

1. Posterior thalamoperforating arteries (Fig. 2.12). The thalamoperforating arteries enter the posterior perforating substance and supply the posterior part of a territory shared with the anterior thalamoperforating arteries (which arise from PComA). These vessels between them (i.e. anterior and posterior thalamoperforating arteries) supply the anterior and posterior parts of the thalamus, posterior optic chiasm and tracts, the posterior limb of the internal capsule, hypothalamus, subthalamus, substantia nigra, red nucleus and the oculomotor and trochlear nuclei, as well as parts of the rostral mesencephalon including part of the cerebral peduncles. They may arise from the terminal BA or from the SCA. An azygos posterior thalamoperforator trunk artery that supplies both thalami is well described and is generally known as the artery of Percheron [8].

There are complex descriptions of the distribution of the thalamoperforating arteries of the PCA

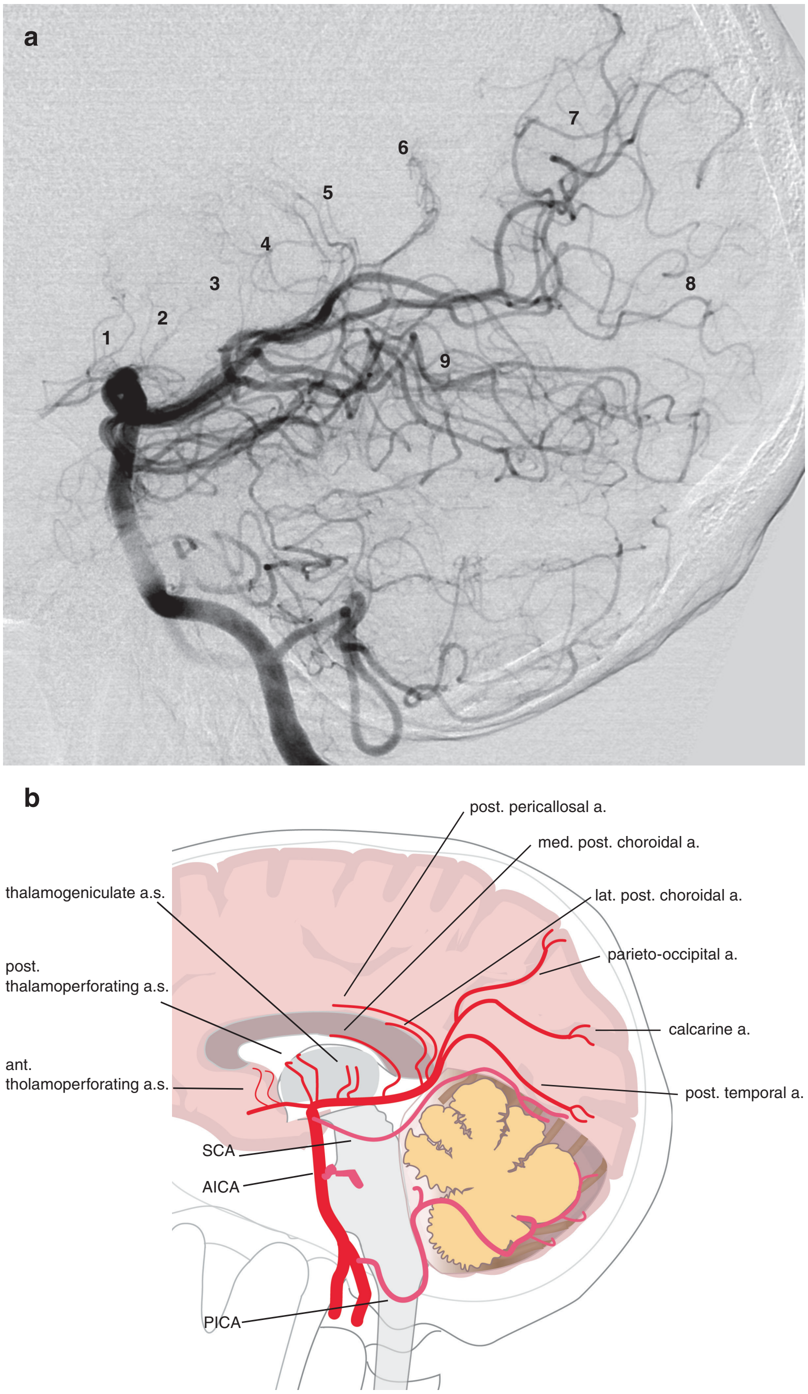

Fig. 2.12 Branches of the posterior cerebral artery, shown on vertebral angiography (**a**) and illustrated in (**b**). In (**a**), the branches have been numbered according to the following keys: *1* ant. thalamoperforating a. *2* post. thalamoperforating a. *3* thalamogeniculate a. *4* med. post. choroidal a. *5* lat. post. choroidal a. *6* post pericallosal a. *7* parieto-occipital a. *8* calcarine a. *9* post. temporal a (Published with kind permission of © Henry Byrne, 2017. All rights reserved)

in the neurosurgical literature. An example of this potential difficulty for the student is the descriptions by Yasargil [9] who divided them into groups: an interpeduncular group, a peri-infundibular group, a perimammillary group and a retro-optic group and a 'simpler' scheme proposed by Pedroza et al. [10] who described perforators that enter the anterior and posterior parts of the posterior perforating substance as paramedian thalamic and superior paramedian mesencephalic arteries, respectively, and the perforators that supply the brain stem posterior to the posterior substance as the inferior paramedian mesencephalic arteries. These descriptions of vessels, which are largely invisible to the endovascular therapist, reflect the complexity of extravascular surgery in this region. For us, their separation into so many different groups is unnecessary, but it remains important to remember that this is an area where embolisation has to be conducted with great caution.

2. Circumflex arteries (short and long). The circumflex arteries (two or more arteries) arise from the distal P1 or proximal P2 and parallel the course of P2 in the ambient cistern (Fig. 2.11). They follow the main trunk around the midbrain and give small branches to the cerebral peduncles and tectum. The long circumflex artery extends to the colliculi and supplies the tectum, tegmentum, cerebral peduncle and geniculate body; the short circumflex artery supplies just the geniculate body, the peduncle and part of the tegmental area. Some authors describe a separate quadrigeminal artery to this territory. The tectum and quadrigeminal plate is also supplied by branches of the SCA.

2.3.3.2 Branches: P2 Section

3. Thalamogeniculate arteries. This group of perforator arteries (usually 8–10) arise distal to the PComA confluence and supply the medial and lateral geniculate bodies, the lateral and inferior part of the thalamus and the posterior internal capsule.
4. Medial posterior choroidal arteries. The medial posterior choroidal artery arises from the medial side of the PCA as 1–3 vessels and run medially to enter the roof of the third ventricle in the velum interpositum. It gives branches in its proximal 'cisternal' course (in the ambient, quadrigeminal and pineal cisterns) to adjacent structures, i.e. the tectum, pineal gland, habenula and medial geniculate body and posterior thalamus.

Within the velum interpositum, it runs forwards to the foramen of Monro,[5] supplying choroid plexus and anastomoses with terminal branches of the lateral posterior choroidal arteries, which have come 'the other way' through the lateral ventricle.

5. Lateral posterior choroidal arteries. The lateral posterior choroidal arteries are a group of arteries that arise from the lateral surface of the PCA, usually distal to the medial posterior choroidal arteries and run superior and anteriorly to enter the choroidal fissure and the lateral ventricle. In their 'cisternal' course (in the ambient cistern), they give branches to supply the cerebral peduncle, the pineal gland, the splenium of the corpus callosum, posterior commissure, tail of the caudate nucleus, lateral geniculate body and thalamus (dorsomedial nucleus and pulvinar). In the ventricle, the arteries pass around the pulvinar and forwards to the foramen of Monro. They supply the choroid plexus and give additional branches to the thalamus.
6. Temporal branches.

The temporal lobe supply from the PCA is normally arranged as:

(a) Hippocampal artery
(b) Anterior temporal artery
(c) Middle temporal artery
(d) Posterior temporal artery

These supply the brain in partnership with the middle cerebral artery cortical branches. The hippocampal artery is found in only two-third of dissections. It arises most proximally and supplies the uncus, hippocampus and dentate gyrus. The middle temporal branch is usually smaller than the anterior and posterior arteries.

7. Meningeal branch or artery of Davidoff and Schechter. A small dural branch that arises from the choroidal or distal cortical branches of the PCA that is, like the medial dural-tentorial artery, only seen on angiography when pathologically enlarged [11]. It supplies the tentorium and posterior falx, but its important relevance to this tutorial is the charming story that the eponymous titles are those of the mentors of the authors who first described it [12], an act of generosity that gives credit to all concerned.

[5] Alexander Monro (1733–1817) Scottish physician who was professor of anatomy in Edinburgh.

8. Posterior pericallosal or splenial arteries. These are usually a group of small arteries rather than solitary bilateral arteries, whose origin varies between the parieto-occipital artery, the calcarine and the posterior temporal branches of the PCA. They initially run posteriorly and then anteriorly and superior to the splenium of the corpus callosum. They anastomose with the terminal branches of the pericallosal artery, and can form an effective collateral supply to the ACA territory.
9. Calcarine artery. This is the artery of supply to the visual cortex. It usually arises from the PCA trunk but may arise from the parieto-occipital artery or posterior temporal artery. Typically, its origin appears inferior to the parieto-occipital artery on a lateral angiogram, and because it runs deep in the calcarine fissure, it appears lateral to the larger parieto-occipital artery on the frontal view. It also supplies part of the cuneus and lingual gyrus as well as the calcarine cortex.
10. Parietal-occipital artery. This is the largest and most superior of the terminal branches of the PCA. It runs in the parieto-occipital fissure and is a cortical branch supplying the cuneus, precuneus and superior occipital gyrus. It may also supply the precentral region (medial surface of the hemisphere) and superior parietal lobule. It often gives an accessory calcarine branch to the visual cortex.

2.4 External Carotid Artery (ECA)

The ECA supplies the tissues of the scalp, skull, face and neck. These include the skin and superficial soft tissues of the head, facial adnexa, dura, cranial nerves and the support structures associated with the special senses, upper airway and alimentary systems. It arises at the level of the superior border of the thyroid cartilage and terminates deep to the neck of the mandible by dividing into superficial temporal and internal maxillary arteries. At its origin, it is situated anterior to the ICA, but as it ascends, it lies more posteriorly and finally lateral to ICA. Thus, on frontal angiography, its origin is medial to the ICA origin and the vessels reverse their relative positions as they run superiorly, but on the lateral view, the ICA is always posterior.

The ECA lies lateral to the pharynx and medial to the sternocleidomastoid muscle. At the angle of the mandible, it lies deep to the posterior belly of digastric and stylohyoid muscles before entering the parotid gland. It divides into the superficial temporal and internal maxillary arteries within the parotid gland. It has eight branches which will be described in their usual sequence from proximal to distal. These are (a) superior thyroid artery, (b) lingual artery (LA), (c) ascending pharyngeal artery (APA), (d) facial artery (FA), (e) occipital artery (OA), (f) posterior auricular artery (PA), (g) superficial temporal artery (STA) (terminal) and (h) internal maxillary artery (IMA) (terminal).

The anterior branches of ECA supply the face and its adnexa, i.e. the FA and the IMA (supported by the superior thyroid and LA). The principal arteries to the superficial structures of the skull, i.e. scalp, and bone are the STA anteriorly (supported by the FA) and the OA posteriorly (supported by the PA). The IMA supplies the anterior deeper structures, i.e. the meninges (via the middle meningeal artery) with the OA supported by the PA and VA, supplying the posterior meninges. In these descriptions, the contributions of the APA have been omitted because its branches supply both anterior and posterior deep structures.

The APA territory is the key to understanding the blood supply to the skull base since it supplies the intermediate zone bordered anteriorly by the IMA territory and posteriorly by the OA and VA. Its embryological heritage from the third branchial arch artery links it to the ICA and so its importance bears no relation to its apparently insignificant size.

2.4.1 Superior Thyroid Artery

The STA arises from the anterior surface of the ECA, just below the greater cornu of the hyoid bone. It describes an inferior concave curve as it runs infero-medially deep to the omohyoid, sternothyroid and sternohyoid muscles to gain the superior apex of the thyroid gland.

2.4.1.1 Branches

1. Infrahyoid artery. A small artery which parallels the hyoid bone medially to supply the thyrohyoid muscle and anastomoses across the midline and with the suprahyoid branch of LA.
2. Branch to the sternocleidomastoid muscle.
3. Superior laryngeal artery. This is the largest branch and supplies the strap muscles above the cricoid ring before it penetrates the cricothyroid membrane and supplies the mucosa of the larynx.
4. Cricothyroid artery. A small branch that runs along the inferior border of the thyroid cartilage and anastomoses across the midline.
5. Terminal branches. The superior thyroid artery terminates by dividing into anterior and posterior branches to supply the thyroid gland.

2.4.2 Lingual Artery

This artery arises from the anterolateral border of the ECA at the level of the greater cornu of the hyoid bone or from a common linguofacial trunk with the FA. It runs forwards and initially loops upwards, where it crosses the hypoglossal nerve and then downwards and forwards on the middle constrictor muscle, deep to the hyoglossus muscle. Finally, it ascends, between the genioglossus muscle and the anterior border of hyoglossus muscle, and runs forwards into the base of the tongue. It gives small branches before terminating in the dorsal artery of the tongue which gives a series of characteristic parallel end arteries.

2.4.2.1 Branches

1. Suprahyoid artery. Posterior to the hyoglossus muscle, it gives this small branch which anastomoses with the infrahyoid artery.
2. Sublingual artery. This branch arises from LA anterior to the hyoglossus muscle and supplies the sublingual gland, adjacent mucosa and anterior mandible.
3. Dorsal artery of the tongue. The dorsal artery of the tongue (or dorsal lingual artery) arises from the horizontal portion of the main trunk and may comprise two or more branches. It runs upwards to vascularise the mucosa at the base of the tongue and sends small branches posteriorly as far as the palatine tonsil.
4. Deep lingual artery. This term (or ranine artery) is used for the most anterior portion of LA which runs parallel to the frenulum, supplying the muscle and mucosa of the tongue.

Though there is a rich anastomosis with proximal branches of the FA at the base of the tongue, there are no anastomoses between the muscular arterial networks and the two halves of the tongue. Embolisation of this section of the lingual artery is thus not advised because of the risk of causing necrosis.

2.4.3 Ascending Pharyngeal Artery (APA)

The APA arises from the posteromedial surface of the ECA (or occasionally from the ICA) at a variable distance after its origin but usually at the same level as the lingual artery. Its trajectory is vertical, lying on the longus capitis muscle, between the carotid sheath and the lateral wall of the pharynx. It supplies the mucosa and muscles of the pharynx, prevertebral muscles and dura of the posterior fossa and craniocervical junction. The trunk divides into anterior and posterior divisions.

2.4.3.1 Anterior Division (Pharyngeal Trunk)

The anterior division or pharyngeal trunk supplies the muscles and mucosa of pharynx in a series of branches:

1. Inferior pharyngeal artery. This supplies the hypopharynx.
2. Middle pharyngeal artery. Supplies the oropharynx and soft palate and takes part in the pharyngeal anastomoses.
3. Superior pharyngeal artery. This is the terminal branch which supplies the nasopharynx and is the major contributor to the pharyngeal anastomosis. Branches anastomose with the accessory meningeal artery in the region of

the foramen spinosum. This is one of several potential anastomotic routes to branches of the ILT. Another is via a branch to the foramen lacerum which is an anastomotic route to the ILT via the recurrent artery of the foramen lacerum. Branches of the superior pharyngeal artery also anastomose with branches of the IMA around the Eustachian tube, i.e. the pterygovaginal and Vidian arteries.

4. Palatine branches are small branches which pass medially on the superior pharyngeal constrictor muscle and supply the soft palate and tonsil and take part in an anastomosis with the descending palatine artery of the IMA and the branches around the Eustachian tube. They may take the place of the ascending palatine artery (from the FA), if it is small.
5. Prevertebral branches are small branches which supply the longus capitis and colli muscles, the sympathetic trunk, the Xth cranial nerve and the lymph node chain as the trunk ascends. They anastomose with branches of the ascending cervical artery.

2.4.3.2 Posterior Division (Neuromeningeal Trunk)

The posterior division or neuromeningeal trunk supplies dura and the lower cranial nerves. It gives two main branches:

1. Hypoglossal artery. This artery is important because of the variety of zones to which it contributes branches. It supplies the hypoglossal cranial nerve in the hypoglossal canal and dura of the anterior posterior fossa and foramen magnum region and contributes to the odontoid arcade [13].

Branches after passing through the hypoglossal canal (Fig. 2.9):

(a) Clival branches which run superiorly onto the clivus and anastomose with the medial clival branch of the MHT.
(b) Branches to the meninges of the posterior fossa which reciprocate their territory with the jugular artery. It anastomoses with the small anterior meningeal artery which is a branch of the VA.
(c) Descending branches which enter the spinal canal through the foramen magnum. They give dural branches to the odontoid arcade. These are best called prevertebral arteries, though this term is sometimes confusingly used for intraspinal arteries that anastomose with the C3 spinal artery of the VA.

2. Jugular artery arises lateral to the neuromeningeal trunk and is the larger of the two main posterior division branches. It runs upwards and medially to enter the cranium through the jugular foramen. In the foramen, it supplies the IXth, Xth and XIth cranial nerves before continuing to supply dura in the posterior fossa (it reciprocates this territory with the hypoglossal artery).

After leaving the foramen, it gives a small medial branch which runs superiorly on the clivus to supply the sixth cranial nerve and continues posterolaterally giving dural branches to supply dura over a variable but usually wider area than branches of the hypoglossal artery. It branches to the dura of the lateral clivus anastomose with the lateral clival artery (meningohypophyseal trunk) and with the dural territories of the middle meningeal, posterior auricular and occipital arteries. From these may arise the artery of the falx cerebelli or the posterior meningeal artery. The meningeal distribution of the neuromeningeal trunk in the posterior fossa varies in extent and can be virtually negligible.

2.4.3.3 Other Branches of the Ascending Pharyngeal Artery

1. Musculospinal arteries arise from the main trunk or the posterior division (i.e. neuromeningeal trunk) in the neck and run posteriorly and upwards. They supply paraspinal muscles (with branches of the ascending cervical artery, in the C3 and C4 regions), the superior sympathetic ganglion and the XIth cranial nerve. These may be evident as a single branch

at the C3 level which some authors term the musculospinal artery and can be seen running posterior to the APA trunks [14]. They take part in the supply of the upper paraspinal muscles and thus potentially anastomose with branches of the deep cervical artery, spinal branches of VA and the ascending cervical artery.

2. The inferior tympanic artery is a small but important artery. It is classically described as a branch that arises from the anterior division (or superior pharyngeal branch) but may arise from the APA trunk or its posterior division. It reaches the middle ear via the inferior tympanic canal (i.e. canal of Jacobson) to supply the cochlear and vestibule, thereby contributing to the anastomotic network of the middle ear cavity.

2.4.4 Facial Artery (FA)

This artery arises from the anterolateral surface of the ECA, above the LA (or from a common trunk with the LA) and medial to the stylohyoid and the posterior belly of digastric muscles. Initially, it lies deep to the mandible and runs alongside the submandibular gland, first upwards and then downwards on its medial and lateral surfaces. It then turns under the inferior border of the mandible (where it is palpable against bone) to climb obliquely across the face, running upwards and forwards. The FA may cross the cheek as a single artery or accompanied by the long facial artery, which arises from its superior surface proximally and runs above to it towards the inner canthus. The long facial artery represents one of several possible branching patterns of the FA on the cheek, sometimes described as jugal pedicles. If multiple, these run a parallel course across the cheek, one above the other.

It terminates at the medial angle of the orbit by forming the angular artery. Branches of the FA are numerous. They arise successively as follows.

2.4.4.1 Branches

1. Ascending palatine artery. This branch arises close to the origin of the FA and supplies the pharynx, soft palate, tonsil and Eustachian tube.
2. Tonsillar artery. The tonsillar artery may be a single artery or represented by two or more small branches. It is usually the dominant supply to the palatine tonsil.
3. Submandibular branches. These arteries are short branches arising as the FA passes around the gland.
4. Submental artery. This branch arises deep to the inferior border of the mandible and gives branches to the submandibular gland, to the mylohyoid and digastric muscles and to the mandible, including a mental branch. It anastomoses across the midline with its counterpart and with the inferior labial branch. A glandular branch may arise as a separate trunk of the FA, proximal to the submental artery origin. During embolisation of the FA, in the context of epistaxis, it is recommended that superselective catheterisation should be performed distal to the origin of this branch artery to avoid damaging the gland.
5. Inferior and superior labial arteries. These run forwards to supply the skin and subcutaneous tissues of the lips. They anastomose across the midline. There is a risk of labial necrosis when embolisation is performed with very small particles in these vessels.
6. Branches to the muscles of the face and the buccinator and masseter muscles. This arterial territory may be configured with a long facial artery so that these branches arise from one of the FA pedicles running superomedially across the cheek towards the inner canthus.
7. Lateral nasal artery. This arises after the superior labial artery to supply the lateral nose. It divides into two (superior and inferior alar arteries) to supply the alar of the nose, i.e. alar cartilages and soft tissue around the nostrils. It anastomoses across the midline with its counterpart.
8. Angular artery. This is the terminal branch of FA and runs superiorly in the angle between the nasion and the medial orbit. It supplies medial cheek and lateral nasal tissues and anastomoses with the dorsal nasal artery (branch of the OphA).

2.4.5 Occipital Artery (OA)

The OA arises from the posterior aspect of the ECA at the level of the FA. It passes upwards, laterally and posteriorly. It crosses lateral to the internal jugular vein and then passes between the mastoid process and the transverse process of the atlas. It gives muscular branches, the transmastoid artery and the stylomastoid artery. These supply muscles at the craniocervical junction, the meninges of the posterior cranial fossa and the middle ear, respectively. The occipital artery passes through the fascia between sternomastoid and trapezius and divides into two superficial branches, one lateral and one medial, to supply the scalp of the posterior cranium. It is a potent route for anastomoses with the vertebrobasilar system.

2.4.5.1 Branches

1. Muscular branches which represent segmental arteries supplying the upper cervical muscles (and nerves and bone). They contribute to the territory of the VA branches at C1 and C2 and anastomose with the spinal arteries of these levels. The muscular branches run posteriorly from their origins with a characteristic proximal section directed superiorly and a longer distal section directed inferiorly. What makes this most striking is that they run parallel to each other. They supply the sternocleidomastoid and other paraspinal muscles in conjunction with branches of the vertebral artery and the deep cervical artery. At C3 and C4 levels, this may include an overlap with the muscular territory of the musculospinal arteries of the APA and at C2, C3 and C4 with the deep cervical artery. A prominent descending muscular branch may be evident arising at the C1 level which runs inferiorly to anastomose with the deep cervical artery at the C3 and C4 levels.
2. Stylomastoid artery. This branch more frequently arises from the posterior auricular artery. See below.
3. Transmastoid artery or artery of the mastoid foramen. This branch is usually identifiable as a single vessel which arises posterior to the stylomastoid process and gives small muscular branches before passing intracranially though its foramen just behind the sigmoid sinus. It supplies the meninges of the posterior fossa, giving branches to the jugular foramen, and dura around the posterior foramen magnum and adjacent posterior fossa. These branches thus reciprocate territory with branches of the jugular and, to a lesser extent, the hypoglossal branches of the APA and posterior meningeal arteries of VA. A small ascending branch to the internal auditory canal can anastomose with AICA through the subarcuate arcade.
4. Lateral meningeal arteries often arise from the OA as it passes posteriorly and upwards. These supply dura in the occipitoparietal region. They pass though small individual foramen and their territory borders on the territory of the posterior branch of the middle meningeal artery.
5. Terminal Scalp Branches. The OA terminates in a series of branches which supply the scalp of the posterior cranium and anastomose across the midline.

2.4.6 Posterior Auricular Artery (PA)

This smaller posterior artery usually arises from the posterior aspect of the ECA, distal to the OA or with it as a common trunk. It passes between the ear and the mastoid process and terminates in superficial auricular and occipital branches to the scalp. It provides branches to the parotid gland, adjacent muscles and is the usual source of the stylomastoid artery.

2.4.6.1 Branches

1. Muscular branches. These supply the adjacent muscles, i.e. sternocleidomastoid, digastric and stylohyoid muscles.
2. Parotid branches. These are usually small and ignored, but may supply the VIIth cranial nerve.

3. Stylomastoid artery. This branch runs upwards into the stylomastoid foramen and supplies the VIIth cranial nerve, the middle ear and the mastoid sinuses. It takes part in the anastomosis within the middle ear with branches of the middle meningeal artery, APA and ICA.
4. Auricular branches supply the posterior pinna.
5. Occipital branches supply the scalp posterior to the ear, in a reciprocal relationship with the OA.

2.5 Terminal Branches of the External Carotid Artery

The ECA divides just above the neck of the mandible and within the parotid gland into the superficial temporal artery (STA) and internal maxillary artery (IMA) (Fig. 2.13).

2.5.1 Superficial Temporal Artery (STA)

The STA is the smaller terminal branch. It supplies skin and superficial scalp muscles in an extensive ramification, anastomosing with the opposite side and the adjacent PA and OA territories (Fig. 2.13). It runs superiorly after emerging from the parotid gland over the posterior portion of the zygomatic arch. Above the arch, it divides into two main branches (frontal and parietal) which run over temporalis deep to the epicranial aponeurosis. These supply muscle, bone and scalp of their named regions. It provides small branches to supply the parotid gland and the temporomandibular joint, as well as the following named branches.

2.5.1.1 Branches

1. Transverse facial artery (or transverse artery of face). This branch varies in size because it reciprocates its territory with the FA. It arises within the parotid gland and runs horizontally anteriorly above the parotid duct to supply superficial facial structures via superior and inferior directed branches.
2. Anterior auricular artery. This small artery arises from the STA below the zygomatic arch and ramifies to supply the anterior external ear.
3. Posterior deep temporal artery supplies the temporalis muscle. It is the smallest of the three possible deep temporal arteries. The anterior and middle deep temporal arteries arise from the IMA.
4. Zygomatico-orbital artery arises above the zygomatic arch and runs anteriorly to supply scalp and the orbicularis oculi muscle. It takes part in the superficial anastomosis of arteries around the orbit.
5. Frontal and parietotemporal scalp arteries are distributed over the anterior scalp and anastomose with their counterparts across the midline. The territory of the frontal branches borders those of the OphA and FA on the forehead and the parietotemporal branches

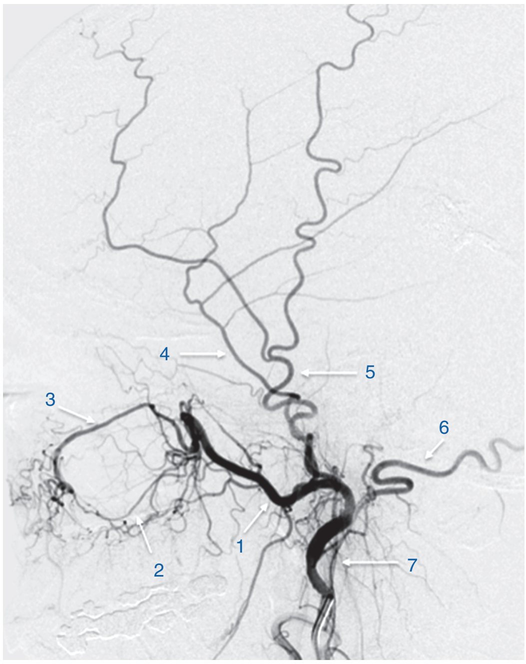

Fig. 2.13 Branches of the distal external carotid artery shown on a lateral angiogram. The numbered arrows mark the following: *1* int. maxillary a.*2* greater palatine a. *3* inf. orbital a. *4* mid. meningeal a. *5* sup. temporal a. *6* occipital a. *7* ascending pharyngeal a

border the PA and OA territories over the lateral cranium.

2.5.2 Internal Maxillary Artery (IMA)

This is the larger terminal branch of the ECA and arises with STA in the parotid gland (Fig. 2.13). It runs medially, deep to the mandible to lie either superficial or deep to the lateral pterygoid muscle before entering the pterygomaxillary fissure and passing into the pterygopalatine fossa (Fig. 2.14). It traverses the fossa and terminates as the sphenopalatine artery. It gives branches to the deep structures of the face, including muscles of mastication, the pharynx, orbit, nose as well as the bone and dura of the anterior skull.

Its 14 named branches, visible on angiography, will be described in the six groups (a–f) used by Djinjian and Merland [15].

(a) Ascending and intracranial arteries, destined to vascularise the meninges, ear and neurocranium
(b) Ascending extracranial arteries
(c) Descending branches which with (e) vascularise the viscerocranium (i.e. the face, mouth and jaw)
(d) Recurrent arteries, which supply structures at the skull base
(e) Anterior branches to the face
(f) The terminal branch, i.e. the sphenopalatine artery

2.5.2.1 The Ascending and Intracranial Arteries

1. Anterior tympanic artery. This arises from IMA close to its origin (but may arise from the ECA termination). It supplies the tympanic cavity, temporomandibular joint and external ear. It is difficult to identify on angiography and runs posteriorly and inferiorly. It gives the deep auricular artery which vascularises the external auditory meatus, as far medially as the tympanic membrane, and branches to the temporomandibular joint and then enters the squamotympanic fissure and supplies the malleus and mucosa of the middle ear.
2. Middle meningeal artery (MMA). The MMA enters the cranial cavity through the foramen spinosum and ends by dividing into frontal and parietal branches (Fig. 2.13). These supply the majority of the convexity meninges. After entering the middle cranial fossa through, it gives the following branches:
   (a) Petrous branch. This small artery supplies dura of the posterior cavernous sinus region and reciprocates with the territories of the petrosquamous branch and the basal tentorial artery of the MHT. It enters the middle ear as the superior tympanic

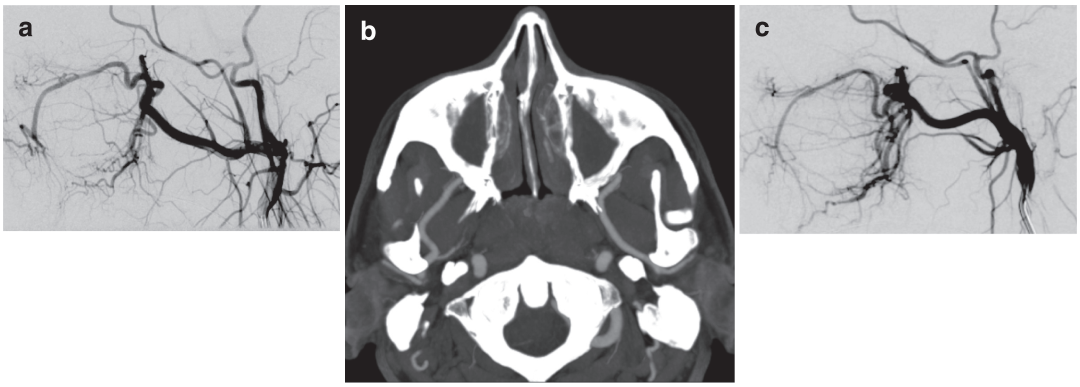

Fig. 2.14 Course of the internal maxillary artery relative to the lateral pterygoid muscle. The arteries are seen on the central MIP reconstructed image from CTA (**b**) and on lateral DSA images, running superficial to the muscle on the right (**a**) and deep to the muscle on the left (**c**)

artery which takes part in the middle ear anastomosis and the supply of the VIIth cranial nerve.

(b) Petrosquamous branches. These are small arteries which arise after the petrous branch to supply dura of the middle fossa floor and part of the anterior tentorium and cavernous sinus. They anastomose with branches of the basal tentorial artery.

(c) Sphenoidal branch. This supplies dura of the anterior part of the middle fossa floor and extends medially to supply the planum sphenoidale as well as sending branches to the cribriform region and anterior falx. A branch may enter the orbit through the superior orbital fissure (meningo-ophthalmic artery).

(d) Meningolacrimal artery. This is an inconstant artery, which enters the lateral orbit via Hyrtl's canal to supply the lacrimal gland.

(e) Temporal branch which is often a large vessel that runs posteriorly on the squamous temporal bone to supply dura of the lateral middle fossa. It contributes to the supply of the tentorium and may supply the posterior falx.

Terminal Branches. The MMA grooves the inner table of the temporal bone to terminate at the pterion by dividing into frontal (anterior) and parietal (posterior) branches which supply bone and dura of the calvarium.

3. Accessory meningeal artery is a small artery which supplies the pharynx, Eustachian tube and a variable amount of the dura of the middle cranial fossa. It arises distal to MMA, but it may arise from MMA, depending on the relationship of the IMA to the lateral pterygoid muscle. The IMA most frequently runs medially, deep to the lateral pterygoid and in this case the accessory meningeal artery arises directly from IMA. If the IMA runs superficial to the muscle, the MMA and the accessory meningeal artery arise from a common trunk (hence the latter's name). The two patterns also correlate with the origins of the inferior alveolar and the middle deep temporal arteries which arise from a common temporodental trunk in the deep variant (Fig. 2.14).

Soon after its origin, the accessory meningeal artery divides into an anterior branch to the pharynx and Eustachian tube and a posterior branch which passes through foramen ovale (anterior to the mandibular nerve (V^3)) and supplies the lateral margin of the cavernous sinus and the Gasserian ganglion.

2.5.2.2 The Ascending and Extracranial Arteries

1. The anterior and middle deep temporal arteries. The anterior and middle deep temporal arteries arise from the IMA. The deep temporal arteries are described in anatomical texts as anterior, middle and posterior but all three are rarely identified on angiograms because the posterior deep temporal artery is small or arises from STA.

The anterior and middle (larger) deep temporal arteries run upwards beneath the temporalis muscle which they supply. The middle deep temporal artery arises from the temporodental trunk of the IMA in the deep variant, as described above. A branch of the anterior deep temporal artery contributes to supply the lateral orbit, anastomosing with the lacrimal branch of OphA.

2.5.2.3 The Descending Branches

1. The inferior alveolar artery (or inferior dental artery) arises from the inferior surface of the IMA, opposite the MMA origin (alone or with the middle deep temporal artery). It traverses the mandibular canal to the mental foramen where it gives the mental artery which terminates in the midline. It gives off dental branches and the mylohyoid artery.
2. Pterygoid branches which supply the pterygoid muscles.
3. Buccal arteries which supply the buccinator muscle, and skin and mucosa of the cheek.
4. Masseteric branches which supply the masseter muscle.

2.5.2.4 The Recurrent Arteries

1. The artery of the pterygoid canal or Vidian artery arises from the IMA in the pterygopalatine fossa and runs posteriorly around the sphenopalatine ganglion (producing a small curve) and then through the pterygoid canal to the nasopharynx. It supplies mucosa of the superior portion of the pharynx near the pharyngeal end of the Eustachian tube and takes part in the anastomosis around the tube. Confusingly, the Vidian artery, with the same territory of supply, can also arise from the MVT of the petrous ICA. It thus can arise from either ICA or IMA and serve as an anastomosis between these arteries.
2. Pterygopalatine artery arises close to the Vidian artery or with it as a common trunk. It is called the pterygovaginal artery by some authors [16] and pharyngeal branch of the internal maxillary artery by others [15]. It passes through the pharyngeal canal (or palatinovaginal canal) which connects the pterygopalatine fossa and the nasopharynx. It supplies mucosa of the pharyngeal roof and around the Eustachian tube and reciprocates its territory with the accessory meningeal and pharyngeal branches of APA.
3. Artery of the foramen rotundum passes backwards to supply the maxillary nerve and adjacent skull base. It runs above the level of the other recurrent arteries and at its origin shows a small bend. It accompanies the maxillary nerve (V^2) with an oblique posterosuperior trajectory on the lateral angiogram and anastomoses with the anterior branch of the ILT. It thus forms a potential collateral route to the ICA.

2.5.2.5 The Anterior Branches

1. The posterior superior alveolar artery (or alveolar-antral artery). This arises from IMA close to the origin of the infraorbital artery or from the proximal section of the infraorbital artery. It runs inferiorly over the tuberosity of the maxilla and gives small branches that supply the molar and premolar teeth, gums of the upper alveolus and mucosa of the maxillary sinus.
2. Infraorbital artery (Fig. 2.13). The infraorbital artery passes through the infraorbital fissure, along the infraorbital groove and canal to the infraorbital foramen. In the canal, it gives a branch to the orbit which supplies the inferior rectus and inferior oblique muscles and the lacrimal sac. Then, the anterior superior alveolar artery which descends to supply the incisor and canine teeth of the upper jaw. After emerging from the infraorbital foramen, it divides into numerous branches which supply the inferior eyelid, the side of the nose, eyelid and upper cheek. These take part in the superficial orbital anastomosis with the angular artery (branch of FA) transverse facial artery (branch of STA) and the dorsal nasal artery from the OphA.
3. The descending palatine arteries (or greater palatine arteries) which run inferiorly and give off lesser palatine arteries destined to supply the soft palate posteriorly and the greater palatine artery which runs forwards to supply the hard palate and terminates in the nasal septum.

2.5.2.6 The Terminal Branch

The sphenopalatine artery is the terminal branch of the IMA. At the medial extent of its course in the pterygopalatine fossa, the IMA enters the sphenopalatine foramen and becomes the sphenopalatine artery to supply the medial and lateral walls of the nasal cavity and adjacent paranasal sinuses.

The sphenopalatine artery gives a pharyngeal branch and then divides within the nasal cavity into lateral nasal and septal nasal arteries.

1. The lateral nasal artery (or posterior lateral nasal artery) divides into two main branches: the artery of the middle concha and artery of the inferior concha. They run forwards and downwards to supply the mucosa of the conchae, the middle and inferior meatuses and the maxillary sinuses.
2. The septal nasal artery is longer than the lateral branches of the sphenopalatine artery and supplies the nasal septum and roof of the nasal cavity. It usually gives branches to supply the superior concha and these anastomose with the anterior and posterior ethmoidal arteries.

An inferior branch runs forwards on the septum to the anterior palatine canal and anastomoses with a branch of the descending palatine artery to form the anterior palatine artery.

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