Chapter 1
Vascular Anatomy of the Brain

Stanislav Naydin, Bianca Marquez, and Kenneth M. Liebman

Introduction

This chapter describes the vascular anatomy of the brain including the arterial supply and venous drainage. The arterial supply is robust, composed of an anterior circulation and posterior that anastomose via the circle of Willis. The anterior circulation is supplied by the internal carotid arteries (ICAs). The ICA terminates below the anterior perforated substance by bifurcating into the anterior cerebral artery (ACA) and middle cerebral artery (MCA). The ACA divides into separate segments derived upon its anatomic relationship to the corpus callosum and the anterior communicating artery. MCA forms as a terminal branch of the ICA to run initially at the floor of the middle cranial fossa. As the artery continues, giving off branches of subsequent diminutive and progressively smaller in caliber vessels. The posterior communicating artery (PCOM) arises from the most posterior segment of the intradural ICA and serves to connect the ICA to the posterior cerebral artery (PCA). PCA arises ventrally from the basilar artery (BA) as terminal branches bilaterally. The vertebral arteries project superiorly and enter through the foramen magnum to enter the dura to become the intradural segment (V4). It is V4 that unites bilaterally at the pontomedullary junction to form the basilar artery (BA). The BA spans from its origin within the prepontine cistern to the interpeduncular cistern where it bifurcates into terminal branches as the PCAs.

The surface of the brain is drained by the three major superficial veins: the superior, the superficial middle, and the inferior cerebral veins. These veins drain

S. Naydin (✉) · K. M. Liebman
Global Neurosciences Institute, Pennington, NJ, USA
e-mail: snaydin@gnineuro.org; kliebman@gnineuro.org

B. Marquez
Drexel University College of Medicine, Philadelphia, PA, USA
e-mail: bsm72@drexel.edu

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into the dural venous sinus system. Dural venous sinuses are intracranial venous channels between the two layers of the dura. Unlike other veins in the body, they run alone, not parallel to arteries. Venous sinuses are valveless, allowing for bidirectional blood flow. This consists of the superior sagittal sinus, inferior sagittal sinus, straight sinus, transvers sinus, sigmoid sinus, occipital sinus, and cavernous sinus.

Internal Carotid Artery

C1, Cervical

The anterior circulation is supplied by the internal carotid arteries (ICA). Several nomenclature schemes exist; Bouthillier segmental nomenclature is most clinically useful and is composed of seven segments ascending with the course of the artery. (Figs. 1.1 and 1.2) The internal carotid artery forms at the bifurcation of the common carotid artery (CCA), most commonly occurring at C4, with some variation. At its origin, the internal carotid artery is somewhat dilated. This part of the artery is known as the carotid sinus or the carotid bulb. The carotid sinus is sensitive to pressure changes in the arterial blood at this level. It is the major baroreceptor site in humans and most mammals.

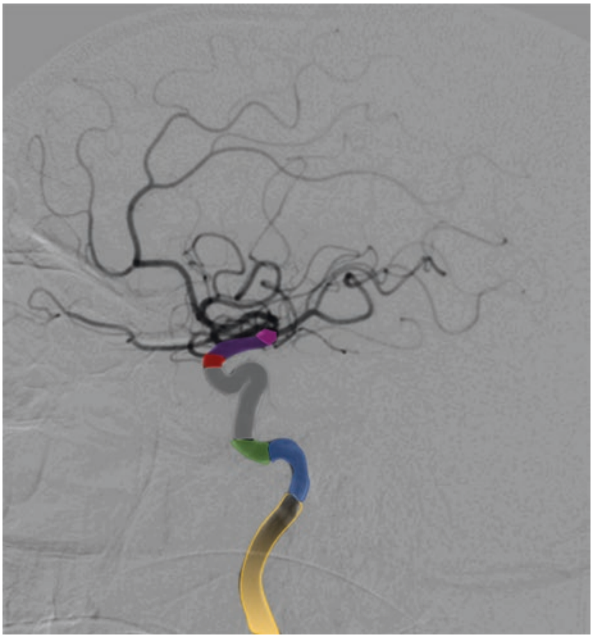

Fig. 1.1 Lateral angiogram of the right internal carotid artery: yellow – C1 (cervical), blue – C2 (petrous), green – C3 (lacerum), gray – C4 (cavernous), red – C5 (clinoidal), purple – C6 (ophthalmic), pink – C7 (communicating)

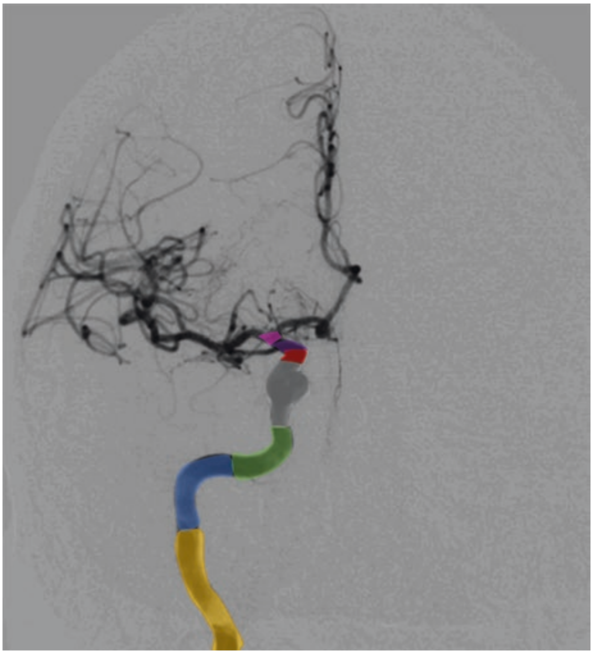

Fig. 1.2 AP angiogram of the right internal carotid artery: yellow – C1 (cervical), blue – C2 (petrous), green – C3 (lacerum), gray – C4 (cavernous), red – C5 (clinoidal), purple – C6 (ophthalmic), pink – C7 (communicating)

The internal carotid runs vertically in the carotid sheath and enters the skull through the carotid canal. The ICA is relatively superficial at its start where it is contained in the carotid triangle of the neck and lies behind and lateral to the external carotid. It courses superiorly where it passes beneath the parotid gland being crossed by the hypoglossal nerve, the digastric muscle, the stylohyoid muscle, the occipital artery, and the posterior auricular artery.

The ICA runs in the carotid sheath medial to the internal jugular vein (IJV). The vagus nerve lies on a plane posterior and lateral to the artery, essentially between and posterior to the ICA and IJV.

Unlike the external carotid artery, the internal carotid artery normally has no branches in the neck.

C2, Petrous

At the skull base, C1 transitions to the C2 portion as it courses through the carotid canal. Here, the petrous ICA ascends, and the artery turns medially in the skull base. The artery continues superiorly toward foramen lacerum not traveling through it as it exits the carotid canal with an anterior trajectory to become C3, the lacerum segment. The petrous portion has three portions: an ascending or vertical part, the genu (bend), and the horizontal portion.

C3, Lacerum

The C3 portion is a short segment that begins above the foramen lacerum (again, not traveling through lacerum) and terminates at the petrolingual ligament, transitioning into the cavernous segment, C4.

C4, Cavernous

The cavernous ICA travels through the cavernous sinus, exiting superiorly through the inner, proximal dural ring. The artery has a distinct trajectory; first, ascending toward the posterior clinoid process, then traveling forward, horizontally by the side of the body of the sphenoid bone, then again curving upward, medial to the anterior clinoid process. This creates an "s" shape referred to as the carotid siphon.

There are two main branches emanating from this portion, the meningohypophoseal artery and the inferior lateral trunk. The artery of Bernasconi and Cassinari, also known as medial or marginal tentorial artery, is a 2 cm long branch from the meningohypophoseal artery. Due to their small size, these arteries are not well depicted on angiography in the absence of pathological increased flow through them. More common disorders that result in engorgement of these arteries, especially the Bernasconi and Cassinari artery, are tentorial meningiomas and tentorial dural arteriovenous fistulas.

The cavernous sinus also gives off small capsular branches that supply the wall of the cavernous sinus.

C5, Clinoidal

C5, the clinoidal segment, starts as the ICA exits the cavernous segment at the proximal dural ring and courses the distance extending to the outer or distal dural ring. This is an important segment because at this point the artery is considered intradural, in the subarachnoid space. Aneurysms arising from this portion are considered intradural and often are referred to as "junctional" aneurysms. Although not common, the ophthalmic artery may arise from this portion.

C6, Ophthalmic

C6, the ophthalmic segment, originates at the distal dural ring and extends to the posterior communicating artery origin. Aneurysms at or above this point that rupture would occupy the subarachnoid space. This forms the superior aspect of the anterior genu, projecting posteriorly and superiorly. Two branches arise from this segment, the ophthalmic artery and superior hypophyseal artery.

C7, Communicating

C7, the communicating segment, spans to include the formation of the posterior communicating artery to the ICA termination, just prior to the anterior perforated substance. It divides into anterior and middle cerebral arteries. This bifurcation occurs in the proximal Sylvian fissure. The C7 segment is bordered by the optic nerve (CNII) in the superior medial direction and oculomotor nerve (CNIII) inferiorly.

Intracranial Branches of ICA

Ophthalmic Artery

The ophthalmic artery (OA) is most commonly the first major intradural branch of the ICA. Researchers have found that in 83.6% of the cases the ophthalmic artery arises above the dura to follow an intradural course. In 6.6% of cases, it arises just above dura, and in 10% it arises below dura to follow a totally or partial extradural course [2–5]. The ophthalmic artery originates from the ICA anteriorly or sometimes anteromedially as the ICA emerges from the cavernous sinus. This artery projects anteriorly to enter the orbit following the optic nerve in the optic canal. The ophthalmic artery travels with the optic nerve (CNII) superiormedially. The oculomotor (CNIII) and abducens nerves (CNIV) pass laterally. Eventually the OA takes a more superior medial path to the medial orbital wall by passing between the optic nerve and the superior rectus muscle.

The first branch, and the most critical branch, is the central retinal artery that vascularizes the retina and is of essential importance for vision [38]. It is one of the smaller branches from the ophthalmic. This artery enters the optic nerve, traveling along the center of the nerve, ending in the eye supplying the blood to the inner retinal layers. The next branch is the lacrimal artery, along several minor arteries to supply the extraocular muscles as well as periosteum in the region. The lacrimal artery follows the course of the lateral rectus muscle along its superior border to supply the lacrimal gland as well as conjunctiva. A notable branch emanating from the lacrimal artery is the recurrent meningeal artery. This branch travels in the reverse direction to pass through the superior orbital fissure to provide anastomosis with the middle meningeal artery. Additional branches off the ophthalmic artery include: supraorbital, medial palpebral, infratrochlear, supratrochlear, and dorsal nasal artery.

The terminal branches also establish extensive anastomoses with branches of the facial, maxillary, and superficial temporal arteries, all of which arise from the external carotid artery. Thereby, the ophthalmic artery establishes a connection between the internal and external carotid artery systems.

Superior Hypophyseal Artery

The superior hypophyseal artery (or arteries) is (are) medial or posterior-medial branch(s) off the internal carotid artery. In 85% of cadaveric dissections it arises within 5 mm of the ophthalmic artery. There are two distinct patterns of this artery. In 42% cases there is a large dominant artery that branches like a candelabra supplying the pituitary stalk, optic nerve (CNII), and chiasm. When a large trunk is not present, two or three smaller, medial projecting vessels are found [5].

Anterior Choroidal Artery

The anterior choroidal artery (AChA) is the last named branch given off the ICA prior to its bifurcation into the anterior cerebral artery and the middle cerebral artery. This artery is relatively small, but AchA can be visualized in 95% of angiograms, at times as a plexus of small vessels. AchA has a distinct "check" shape at its origin off the ICA (Fig. 1.3). The cisternal segment projects toward the choroid plexus of the lateral ventricle. The artery first courses postero-medially below the optic tract with the temporal lobe uncus lying inferior-laterally and then taking a more posterior lateral course after curving around the cerebral peduncle within the

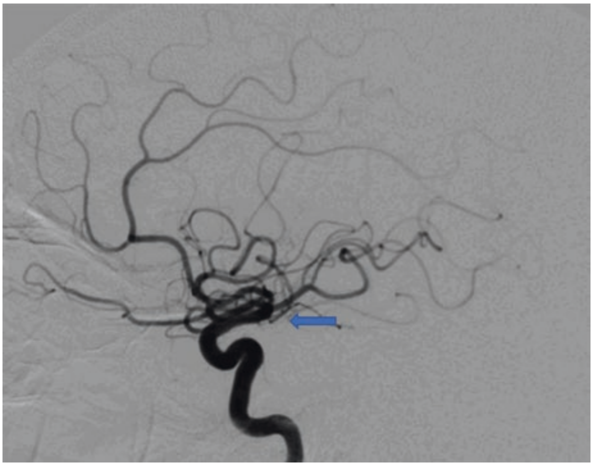

Fig. 1.3 Lateral ICA angiogram; blue arrow pointing to the "check" sign at the origin of the anterior choroidal artery

crural cistern. After continuing to the lateral geniculate body, the AchA generally takes a sharp angle to enter the temporal horn through the choroidal fissure.

As the distal segment or intraventricular AchA continues at the choroidal fissure, it wraps around the pulvinar of the thalamus. Following the choroid plexus in the supracornual cleft. It may continue anteriorly here for a short distance and some have reported AchA extension to the foramen of Monro to anastomose with the medial posterior choroidal artery [6].

Anterior Cerebral Artery

The ICA terminates below the anterior perforated substance by bifurcating into the anterior cerebral artery (ACA) and middle cerebral artery (MCA). The ACA is divided into separate segments derived upon its anatomic relationship to the corpus callosum and the anterior communicating artery.

A1, Pre-communicating

The proximal A1 is the pre-communicating or at times referred to as the horizontal segment. A1 starts immediately from the bifurcation of the ICA forming and extending to the anterior communicating artery complex. The A1 courses straight and medially to the interhemispheric fissure. A1 passes over the optic nerve (CNII) 70% or optic chiasm in 30% of cadaveric dissections. The A1 connects with the anterior communicating artery (Acom) just inferiorly or at the interhemispheric fissure.

The A1 segment provides small perforating branches in the inferior direction for blood supply to the optic chiasm, hypothalamus, and anterior corpus collosum. The horizontal segment also contributes the medial lenticulostriate arteries in the posterosuperior direction through the anterior perforated substance to supply globus pallidus and medial portion of the putamen. These perforating arteries are unpaired with little to no collateral flow, any occlusion or decrease in flow leaves little opportunity for collateral flow to provide adequate perfusion [7].

Anterior Communicating Artery

Anterior communicating artery (ACom) is a horizontal interconnection between the bilateral ACAs within or inferiorly to the interhemispheric fissure. This provides a clinically significant anastomosis between the two hemispheres and ICAs, comprising the anterior portion of the circle of Willis. Along with A1, ACom can contribute perforating arteries to the basal ganglia. There are no cortical branches formed at ACom.

A2, Post-communicating

The A2 segment continues medially and anteriorly as the infracallosal segment also known as the post-communicating segment. This portion travels from ACom along the rostrum of the corpus callosum to the genu in a vertical direction.

A2 is commonly the site of the formation of the recurrent artery of Heubner. Cadaveric dissections demonstrate variance up to 45% from A1 and 5% from ACom. This is the largest and only named branched artery gaining its name from the course it takes by retracing the ACA in the reverse direction at a sharp angle to terminate dorsally and laterally to the carotid terminus. At times, Heubner will continue to the anterior perforated substance close to or just anterior to the Sylvian fissure [6, 8].

Additional branches of the ACA are generally small and demonstrate irregularity, as a result named after the areas that are supplied. These include the orbital, frontal, orbitofrontal, and frontopolar arteries. The orbitofrontal artery, frequently the first branch of the A2 segment, passes anteriorly and inferiorly toward the anterior cranial fossa to terminate in the orbitofrontal cortex. The orbitofrontal artery provides bloody supply to gyrus rectus, medial orbital gyrus, olfactory bulb, as well as tract. When identifiable, the frontopolar artery can be seen forming below the corpus collosum to flow anteriorly to the frontal pole to supply the ventromedial surface of the frontal pole as well as parts of the frontal convexity.

A3, Precallosal

The ACA continues superiorly to wrap around the genu of the corpus callosum to become the precallosal segment. A3 runs until the artery turns directly posterior to lie above the corpus collosum within the interhemispheric fissure. A3 terminates as a bifurcation into pericallosal and callosomarginal arteries, at times referred to as the A4 and A5 segments, respectively. The ACA continues as the pericallosal artery to course over the body of the corpus callosum. The callosomarginal artery passes in the cingulate gyrus and also continues posteriorly. Both of these terminal branches run under the falx cerebri and provide collateral circulation with the MCA and PCA territories; referred to as the "watershed zone."

Pericallosal Artery

The pericallosal artery is the distal portion of the ACA that courses over the superior surface of the body of the corpus callosum in the pericallosal cistern. It gives off many small branches to the corpus callosum.

Some authors describe the pericallosal artery as the entire distal portion of the ACA beginning at the anterior communicating artery, segments A2–A5. This includes the portion anterior to the lamina terminalis, the rostrum, and genu of the

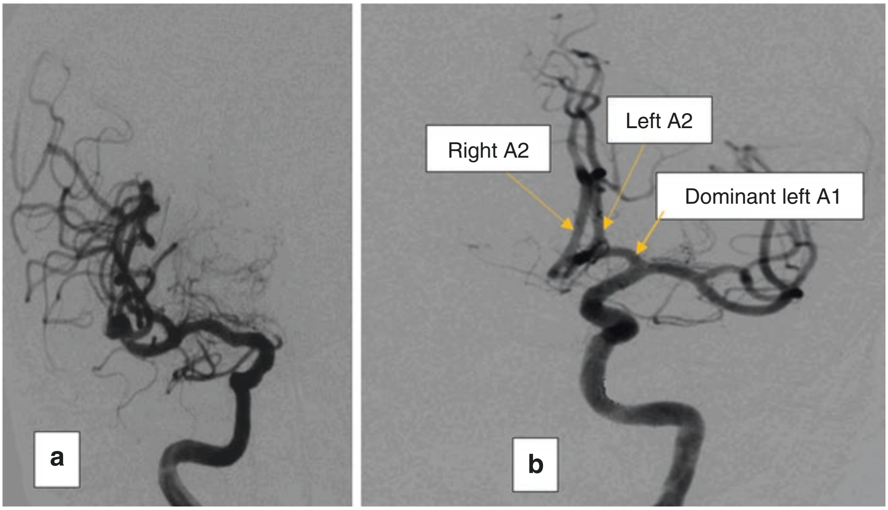

Fig. 1.4 (**a**) Selective right internal carotid artery angiogram depicting an absent right A1. (**b**) A selective left internal carotid artery angiogram. One can see the left A1 is quite robust filling both A2s, right and left

corpus callosum [38, 39]. Other authors define it as the artery created at the bifurcation of the ACA near the genu of the corpus callosum after giving off the callosomarginal artery, segments A3–A5 [38].

ACA can exist as several different normal variants. A1 can be hypoplastic on one side with the contralateral side compensating (Fig. 1.4). The ACA can also form as an azygous artery. In this case a single large artery running in the interhemispheric fissure provides necessary bilateral vasculature.

Middle Cerebral Artery

The middle cerebral artery (MCA) forms as a terminal branch of the ICA to initially run along the floor of the middle cranial fossa. As the artery continues, giving off branches of subsequent diminutive and progressively smaller caliber vessels, the MCA nomenclature changes.

M1, Horizontal

The most proximal MCA segment from the ICA branch point is the M1 or horizontal segment running almost perfectly perpendicular from the ICA to its bifurcation and then the Sylvian fissure. The optic chiasm lies medially, and the olfactory trigone remains anterior. M1 consists of the pre-bifurcation segment and post-bifurcation segment, approximately 10 mm from ICA terminus. Studies have shown that division of M1 results in a bifurcation in 78%, trifurcation in 12%, and > 3 trunks in 10% of cases. Following this division, the arteries continue to travel in parallel just below the anterior perforating substance to the genu of the Sylvian fissure.

The pre-bifurcation portion of M1 produces the anterior temporal artery tracking anteriorly and inferiorly to run over the temporal lobe to provide vascular supply to the anterior third of the superior, middle, and inferior temporal gyri [12].

It is the proximal M1 segment that gives off the lateral lenticulostriate arteries which serve as perforating arteries supplying the internal capsule via the perforating substance. More distally, still within the horizontal segment, the lateral lenticulo-striate arteries form and ascend in the external capsule to pass through the basal ganglia medially to supply the caudate nucleus.

M2, Insular

The M2 segment begins in the Sylvian fissure at the genu where the post-bifurcation segment turns superiorly in its course at the limen insulae and continues to pass over around the insula. Along this path dividing further into up to eight stem arteries which travel around the insula in the cerebrospinal cistern to become M3 (Fig. 1.5).

M3, Opercular

M3 or opercular segment is the superior portion of the circular sulcus as M2 courses more laterally within the Sylvian fissure and to the surface of the lateral cerebral fissure. The MCA continues to form M3 branches which travel to frontal, parietal, and temporal operculum. The artery forms a loop over the top of the Sylvian fissure as the branches turn laterally to exit the fissure to run over the hemisphere.

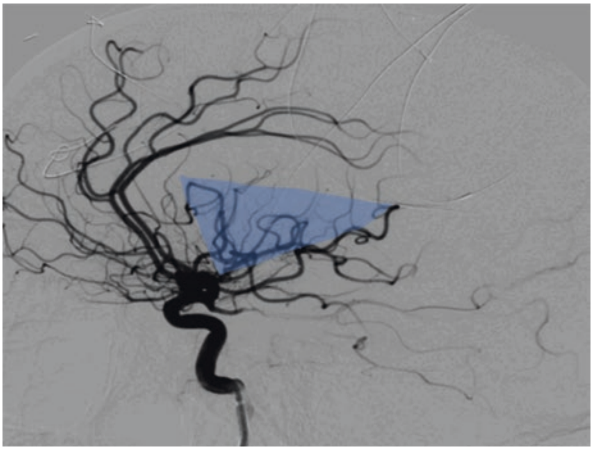

Fig. 1.5 Lateral view cerebral angiogram. Internal carotid artery injection with the blue shaded area demonstrating filling of Sylvian triangle within Sylvian fissure by branches of MCA

M4, Cortical Branches

M4 is the distal most portion of the MCA forming the terminal branches which begin at the surface of the Sylvian fissure as the distal M4 branches to pass over the cortical surface. Up to 12 named branches can be observed. These are generally divided into three groups: anterior, intermediate, and posterior branches based on the territory that they supply.

Anterior Branches

The anterior group of branches consists of the orbitofrontal and prefrontal arteries that supply the frontal lobe in an overlapping pattern, with the prefrontal forming a candelabra to provide arterial vasculature to lateral frontal lobe in front of the Sylvian triangle. The orbitofrontal arteries, as their name implies, give supply to the inferior surface of the frontal lobe overlying the orbits.

Intermediate Branches

Intermediate branches span the distance between the precentral sulcus and postcentral sulcus with nomenclature derived from each branch's relationship to the sulci. Precentral, also referred to as the prerolandic artery, courses superficially between the posterior part of the frontal lobe and anterior edge of the parietal operculum supplying small branches within the precentral and central sulci.

The central sulcus is further supplied by a dedicated branch, or rolandic artery (at times several branches), that project between the precentral and postcentral sulci.

Finally, the postcentral sulcus artery flows within the corresponding sulcus and continues in the intraparietal sulcus.

Posterior Branches

Posterior branches of M4 provide vasculature to the remaining MCA territory consisting of parietal, temporal, and occipital lobes named for each corresponding lobe.

The posterior parietal artery travels in the posterosuperior path over the end of the Sylvian fissure and then anteriorly along the posterior of the parietal lobe. The posterior parietal artery then continues to the supramarginal gyrus.

The temporo-occipital artery travels in the superior temporal sulcus in the dorsal direction to the superior temporal gyrus with branches to the occipital region.

The posterior temporal artery passes the superior temporal gyrus to run superiorly with a sudden downward turn into the superior temporal sulcus to continue to the inferior temporal sulcus to provide vasculature to the posterior portion of the temporal lobe.

Medial Temporal Artery

The medial temporal artery crosses the superior temporal gyrus to supply the inferior temporal sulcus.

Posterior Cerebral Artery

The posterior cerebral artery (PCA) arises ventrally from the basilar artery as terminal branches bilaterally, traveling in either the interpeduncular cistern or the suprasellar cistern.

P1, Pre-communicating

The most proximal segment forms at the basilar artery junction (P1) called the pre-communicating or mesencephalic segment. P1 can form in the interpeduncular cistern, posterior to the dorsum sellae or inferior to the third ventricular floor in the suprasellar cistern. P1 extends to the anastomosis with the posterior communicating artery. P1 follows the midbrain and curves around it. At times the PCA can be found in a variant type. In a fetal origin of the posterior cerebral artery the posterior communicating artery (PCOM) branching off the ICA is larger than the posterior cerebral artery (PCA) originating from the basilar. Subsequently the larger fetal type supplies the bulk of the blood to the PCA distribution. Alternatively, the PCA can come directly off of the ICA and there is no PCA from the basilar. This is a common variant in the posterior cerebral circulation, estimated to occur in 20–30% of individuals (Figs. 1.5 and 1.6).

P1 provides perforating arteries to the brainstem and thalamus, the posterior thalamoperforating arteries (PTPAs). The PTPAs initially course posterosuperiorly within the interpeduncular fossa. They pass in the posterior perforated substance posterior to the mammillary bodies. Up to 42% of studied specimens demonstrated that the posterior thalamoperforating arteries were the largest branches from P1 [16]. It has been observed in 80% of occurrences that the posterior thalamoperforating arteries have anastomoses within themselves [17].

The artery of Percheron (AoP) is a rare anatomical variation of the posterior circulation in which a single arterial trunk arises from the posterior cerebral artery (PCA) to supply both sides of the thalamus and midbrain.

P2, Ambient

The second segment, P2, gains its name from the ambient cistern within which it lies. The ambient segment starts from the PCOM branch point spanning to the dorsal midbrain. Its path is parallel to the optic tract and basal vein of Rosenthal.

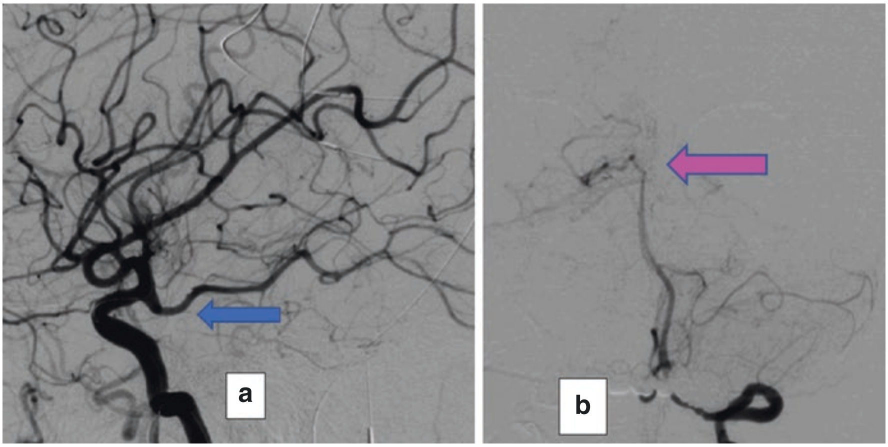

Fig. 1.6 (**a**) A lateral angiogram of the left ICA. The blue arrow points to the PCA emanating from the ICA. (**b**) Angiogram is a left vertebral injection. The pink arrow points to where the left PCA should project originating off the basilar apex. It is absent, again arising from the ICA

Perforating Arteries

Thalamogeniculate perforating arteries generally branch from P2, with up to 20% originating from P3. The number of perforating branches has a high variance from 2 to 12. Cadaveric dissection demonstrates the formation of these vessels in 66% of cases as individual vessel, and in the remaining as a common trunk that then branches into small perforating vessels.

The peduncular perforating arteries branch from P2 and again have many variations, from zero to six vessels, to supply the cerebral peduncle [15].

The medial posterior choroidal artery has been shown to originate from P2 in 70% of cadaveric dissections, from P1 in 12%, or the parietooccipital artery in 12%. However, it is worthwhile to mention that of cadavers investigated it was only present in 10–45% of cases [15]. From the parent vessel the medial posterior choroidal artery circumvents the brainstem to then flow in the superior medial direction through the roof the third ventricle running in between the bilateral thalami to supply the choroid plexus in the lateral ventricle by passing through foramen of Monro.

Lateral posterior choroidal arteries most commonly form as several vessels from P2. The lateral posterior choroidal arteries enter the choroid plexus of the temporal horn via the choroidal fissure to wrap around the thalamic pulvinar in the lateral ventricle. These small perforating arteries anastomose with both the medial posterior choroidal arteries and anterior choroidal artery from ICA.

Cortical

P2 has two commonly accepted cortical artery branches. The first branch is the anterior temporal artery which at times can also exist as several branches. In either case, the artery projects in the anterolateral direction to pass under the hippocampal gyrus. The anterior temporal artery provides anastomoses with the MCA with its anterior temporal branches [14].

The second cortical branch from P2 supplies the inferior posterior temporal lobe. This branch courses from the middle of P2 to follow the hippocampal gyrus laterally. Along its path it gives off several small branches that can extend as far as the occipital cortex to supply the visual cortex [14].

P3, Quadrigeminal

The PCA continues to curve around the midbrain on the lateral aspect and then takes on a medial course. The two sides project toward each other. P3 lies within the perimesencephalic cistern with the transition from P3 to P4 occurring as the artery reaches the calcarine fissure.

P4, Calcarine

The PCA terminates as P4 (calcarine segment) within the calcarine fissure as it bifurcates into terminal branches, medial and lateral occipital arteries.

The medial PCA trunk further branches into smaller splenic arteries to supply the dorsal surface of the corpus callosum. These provide anastomoses with the ACA via its pericallosal branches, earning the name posterior pericallosal artery.

The parietooccipital artery and calcarine artery form together as a fork of the medial PCA trunk. The parietooccipital artery continues in the superior lateral direction into the parietooccipital sulcus of the occipital lobe to supply the visual cortex. The sibling vessel, the calcarine artery, also takes a posterior path. It courses deep in the calcarine sulcus to supply the visual cortex.

Posterior Communicating Artery

The posterior communicating artery (PCom) arises from the most posterior segment of the intradural ICA and serves to connect the ICA to the posterior cerebral artery (PCA), serving as a vital anastomosis of the anterior and posterior circulation. The PCom courses posteriorly just below the edge of the tentorium, above the oculomotor (CN III) nerve (an essential anatomic relationship). Several tiny branches are given off by the PCom. These thalamoperforating arteries form in many variations. Generally, the largest of these is the premamillary, also named the anterior thalamoperforating artery. These also include the anterior and posterior thalamoperforating arteries that traveling through the anterior perforated substance to provide blood supply to the posterior limb of the internal capsule, anterior thalamus, posterior hypothalamus, anterior one-third of the optic tract, and subthalamic nucleus [1]. It is worthwhile to note that these perforating branches render blood supply to the wall of the lateral ventricle.

Basilar Artery

The vertebral arteries project superiorly and enter through the foramen magnum to enter the dura to become the intradural segment (V4). It is V4 that unites bilaterally at the pontomedullary junction to form the basilar artery (BA). The BA spans from its origin within the prepontine cistern to the interpeduncular cistern where it bifurcates into terminal branches as the PCAs. The BA takes this course with its location being medial and posterior to the clivus and running anterior to the pons. Along the BA's course, the abducens nerves (CNVI) course directly in front, at the lower pontine border. The oculomotor nerve (CNIII) also courses anteriorly to the BA at the upper pons.

Labyrinthine Arteries

The labyrinthine arteries provide vascular supply to the internal acoustic meatus and inner ear via long projections. These projections can be seen coursing into the internal acoustic meatus with the facial nerve (CNVII) and vestibulocochlear nerve (CNVIII). These arteries form with tremendous variation, 16% as direct projections from BA. The remainder, as branches from other branches of BA, 25% from superior cerebellar and 45% from anterior inferior cerebellar arteries.

Cerebellar Arteries

Posterior Inferior Cerebellar Artery

The posterior inferior cerebellar artery (PICA) is the largest artery that provides arterial supply to the lower medulla, inferior aspects of the fourth ventricle, tonsils, vermis, and inferolateral cerebellar hemisphere. This artery has tremendous variability and is formed from the distal vertebral arteries above the foramen magnum at or below the level of the inferior olive in 80% of studied cases [45].

PICA forms from the bilateral vertebral arteries anterior-laterally and follows the medullary cistern as the anterior medullary segment. PICA then continues in the cerebellomedullary fissure as the lateral medullary segment in the posterior direction, often passing between the roots of the glossopharyngeal (CNIX), vagus (CNX), and spinal accessory (CNXI) nerves. Here, PICA makes its first of two loops. It is not uncommon for the loop to extend below the foramen magnum and return to run intracranially. PICA continues anteriorly along the lateral surface of the medulla. The next segment (supratonsilar) forms when PICA reaches the posterior border of the medulla as it passes superiorly, posterior to the medullary velum, sometimes across the cerebellar tonsil. Finally, the PICA completes a second loop to terminate by dividing into hemispheric branches: tonsilohemispheric and vermian branches.

Anterior Inferior Cerebellar Artery

Anterior inferior cerebellar artery (AICA) is a small artery that arises from the proximal BA in up to 30% of cases, arising as two or three branches. The artery travels within the cerebellopontine angle cistern continuing posteriorly, inferiorly, and laterally. As AICA courses, the facial nerve (CNVII) remains posterior-lateral to the artery. As discussed above, AICA can give off labyrinthine arteries. One of the more common variants is an absent right PICA with a compensatory robust AICA on the ipsilateral side, sometimes called AICA-PICA [46] (Fig. 1.7).

Superior Cerebellar Artery

The superior cerebellar artery (SCA) forms on both sides of the basilar artery distally, just prior to PCA formation. SCA courses laterally within the prepontine cistern along with the oculomotor nerve, to the ambient cistern and turning posteriorly. SCA continues over the middle cerebellar peduncle and turns medially towards the SCA of the contralateral side near the midline, in the quadrigeminal cistern. The SCA provides vascular supply to the superior portion of the cerebellum

Fig. 1.7 A/P projection of a right vertebral artery angiogram. There is no right PICA, and the red arrow points to a compensatory robust AICA on the ipsilateral side

as well as the inferior vermis. SCA originates to pass below the oculomotor nerve (CNIII) and then passes between the trochlear nerve (CNIV) and the trigeminal nerve (CNV). SCA is in contact with the trigeminal nerve in 50% of studied specimens [18].

The basilar artery gives off many important perforating branches. In the prepontine cistern, it produces the median pontine perforating, paramedian pontine perforating, and later pontine arteries. The former two are given off posteriorly to travel dorsally and penetrate the pons all the way to the fourth ventricular floor. The lateral pontine arteries are also called circumferential branches because of the path in which they travel. They also forming on the posterior aspect but then wrap around the brainstem giving off many tiny perforating arteries to supply the brainstem and pons [19].

Remnants of the Embryonic Arterial System

The persistent trigeminal artery (PTA) is a rare remnant of the embryonic circulatory system that unites the proximal intracavernous segment of internal carotid artery (ICA) with the middle or distal portion of the basilar artery (BA). The origin of the PTA is usually in the posterior or lateral surface of the intracavernous ICA just proximal to the origin of the meningohypophyseal trunk (Fig. 1.8).

A persistent hypoglossal artery is another persistent carotid-vertebrobasilar anastomoses (Fig. 1.9). It is second in frequency to the trigeminal artery. It arises from the distal cervical ICA, usually between C1 and C3. After passing through an enlarged hypoglossal canal, it joins the basilar artery inferiorly. If large, the ipsilateral vertebral artery and PCOM are often hypoplastic or absent.

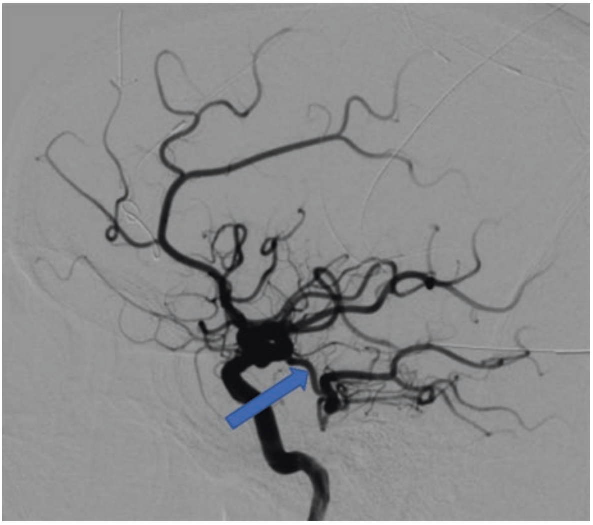

Fig. 1.8 Lateral angiogram of the ICA. The blue arrow points to the persistent trigeminal artery, a rare remnant of the embryonic circulatory system that unites the proximal intracavernous segment of ICA with the middle or distal portion of the basilar artery

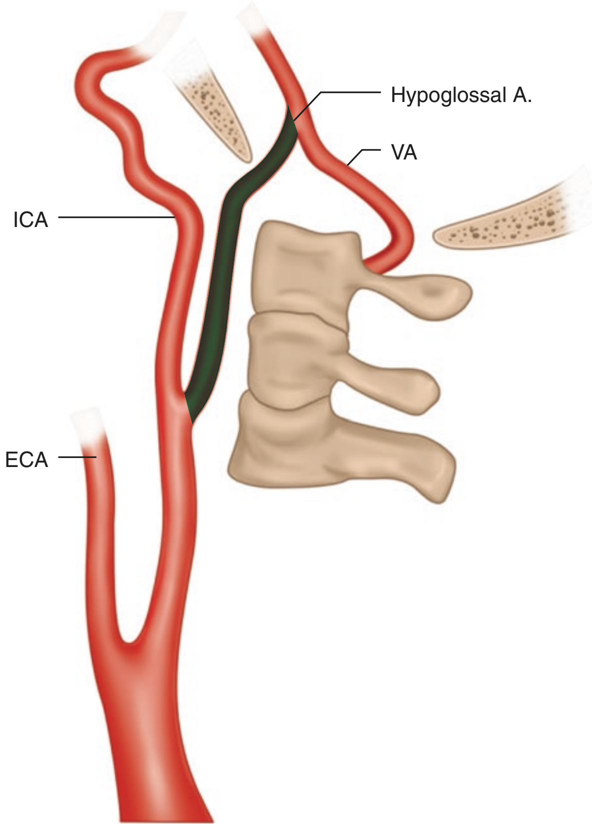

Fig. 1.9 Diagram of persistent hypoglossal artery (in yellow) from internal carotid artery (ICA) to posterior circulation anastomosis with vestibular artery (VA) often hypoplastic or absent

A persistent otic artery is one of the persistent carotid-vertebrobasilar anastomoses, although there is considerable controversy in regard to its existence. It is said to arise from the C2 (petrous) segment of the internal carotid artery, within the carotid canal. This artery emerges from the internal acoustic meatus and joins the basilar artery, inferiorly.

The first three arteries are also known as presegmental arteries and are named after the cranial nerves they follow [40, 41].

The persistent proatlantal artery can be subdivided into two types depending on its origin. Type I, also known as the proatlantal intersegmental artery, arises from the internal carotid artery. This is similar to the hypoglossal artery, but instead of heading for the hypoglossal canal, it joins the vertebral artery at the V4 segment through the foramen magnum [40]. Type II arises from the external carotid artery or rarely from the common carotid artery, and joins the V3 segment of VA [42, 43] (Fig. 1.10).

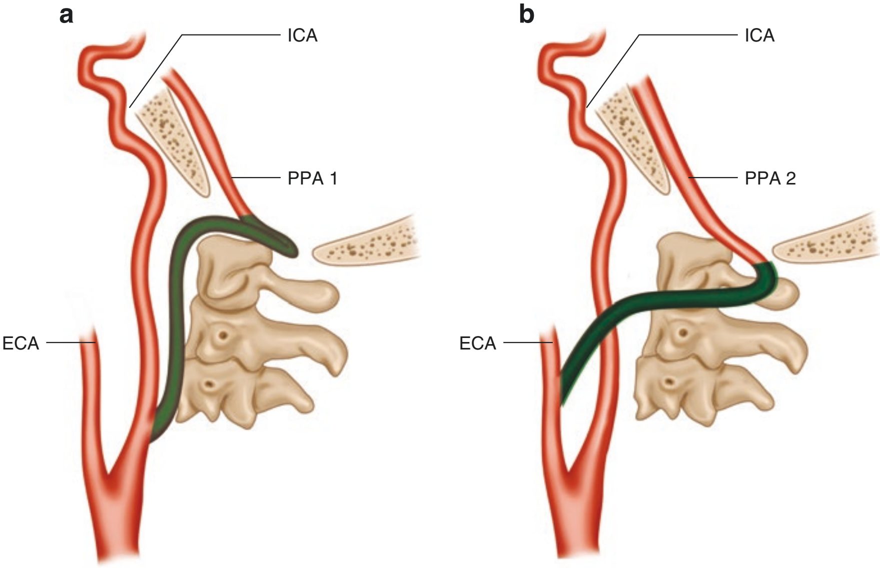

Fig. 1.10 (**a**) Diagram of Type I persistent proatlantal artery (PPA1) (yellow) or proatlantal intersegmental artery arises from the internal carotid artery to join the vertebral artery at the V4 segment through the foramen magnum. (**b**) Diagram of Type II persistent proatlantal artery (PPA 2) (yellow) arises from the external carotid artery or rarely from the common carotid artery to join the vertebral artery at the V3 segment through the foramen magnum

Venous System

Superficial Veins

The surface of the brain is drained by the three major superficial veins: the superior, the superficial middle, and the inferior cerebral veins. The superior cerebral veins drain the superior, lateral, and inferior surfaces of the hemisphere and then drain into the superior sagittal sinus. The middle cerebral vein is located on the lateral surface of each hemisphere, running along the lateral sulcus and to the cavernous sinus. The middle cerebral vein has two important anastomoses: the vein of Trolard and the vein of Labbe. These veins connect to the superior sagittal sinus and the lateral transverse sinus, respectively. Finally, the inferior cerebral vein, as its name implies, drains the inferior surface of the cortex and empties into the cavernous and transverse sinuses.

Dural Venous Sinuses

Dural venous sinuses are intracranial venous channels between the two layers of the dura mater (endosteal layer and meningeal layer). Unlike other veins in the body, they run alone, not parallel to arteries. Venous sinuses are valveless, allowing for

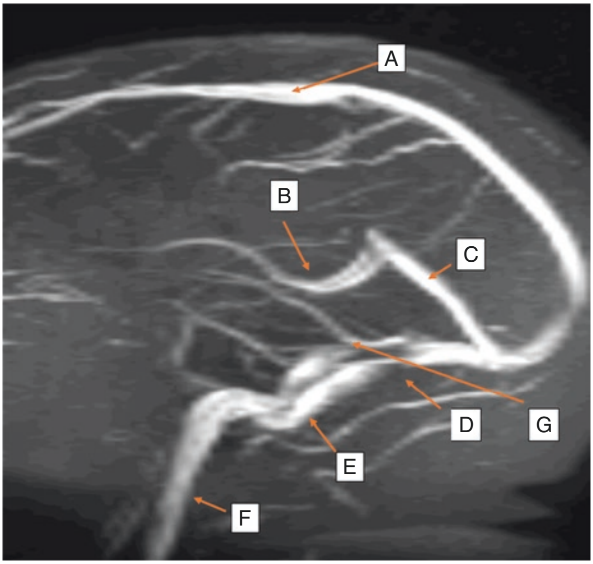

Fig. 1.11 Lateral magnetic resonance venography (MRV). A superior sagittal sinus, B internal cerebral veins, C straight sinus, D transverse sinus, E sigmoid sinus, F jugular vein, G vein of Labbe

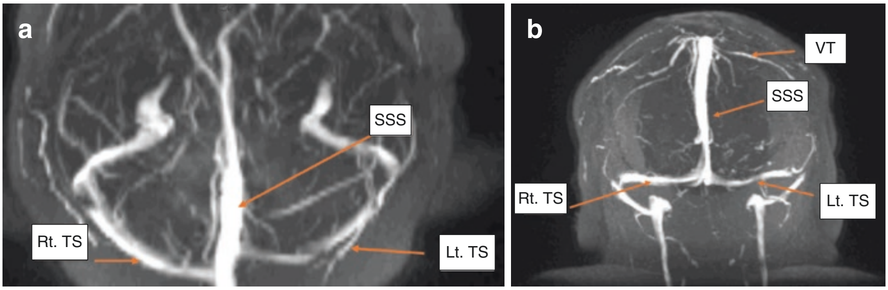

Fig. 1.12 (**a**) An axial MRV, (**b**) coronal MRV: The right transverse sinus (Rt. TS) is dominant and is a continuation of the superior sagittal sinus (SSS). The left transverse sinus (Lt. TS) is the continuation of the straight sinus. Vein of Trolard (VT) draining into the SSS

bidirectional blood flow in intracranial veins. The draining territories of intracranial veins are different from those of major cerebral arteries [36] (Figs. 1.11 and 1.12).

Superior Sagittal Sinus (SSS)

The superior sagittal sinus is formed by the superior portion of the falx cerebri, a fold in the meningeal dura that separates the two hemispheres. Its course begins in the midline of the shallow groove on the inner table of the cranium and grows larger as it traverses posteriorly. Next, it extends backwards from the crista galli (attachment point of the falx cerebri) all the way to the confluence of the sinuses, and thereafter turns right to become continuous with the right transverse sinus. It receives blood from the veins of the frontal sinus anteriorly and the veins of the nasal cavity (foramen caecum). Additionally, the sinus connects to the superior cerebral vein, the parietal emissary veins, and the venous lacunae.

SSS drains blood from the lateral aspects of anterior cerebral hemispheres to the confluence of sinuses. Cerebrospinal fluid drains through arachnoid granulations into the superior sagittal sinus and is returned to venous circulation.

Ligation of the anterior third of the superior sagittal sinus is generally presumed to be safe and is commonly performed to gain access to the anterior skull base. In contrast to this teaching, studies have demonstrated complications associated with this maneuver. One study describes a morbidity of 8.06% and a mortality of 1.6% from bifrontal venous infarcts [23]. It is important to understand the drainage pattern of the frontal veins draining into the anterior third of the SSS before ligating, especially for tumors of the anterior skull base [28].

The anterior portion of this sinus is atretic in 1% of the population.

Inferior Sagittal Sinus

The inferior sagittal sinus (ISS) runs in the free margin of the falx cerebri and joins posteriorly with the great cerebral vein of Galen. ISS receives blood from the falx cerebri and small veins near the medial surface of the cerebral hemispheres. The sinus drains the blood coming from the deeper medial surface of the cerebrum. ISS joins the great cerebral vein of Galen (VoG) progressing into the straight sinus.

Straight Sinus

The straight sinus is formed by the junction of the inferior sagittal sinus and the VoG. As it courses posteriorly at the junction of the falx cerebri and the tentorium cerebelli, some superior cerebellar veins drain into the straight sinus. The straight sinus then continues its course posterior-inferiorly to drain into the confluence of the sinuses. The exact drainage of is variable, draining into the confluence of sinuses 56% of the time, into the left transverse sinus 21%, and right transverse sinus 13% of the time. The confluence is located deep into the internal occipital protuberance, receiving blood from the straight sinus, the great cerebral vein of Galen, and the superior cerebellar vein [31].

Transverse Sinus

The transverse sinus (TS) begins at the confluence of the sinuses by the internal occipital protuberance. The sinus has right and left segments. Most commonly, the right segment is a continuation of the superior sagittal sinus and is the larger of the two. The left segment is usually continuous with the straight sinus. Each portion (right and left) travels along the tentorium cerebelli. In greater detail, both portions of the transverse sinus traverse anteriorly and laterally to eventually reach the posterolateral end of the petrous bone. From the petrous bone TS becomes the sigmoid sinus, which continues as the jugular bulb in the base of the skull, receiving blood from the inferior cerebral, inferior cerebellar, diploic, inferior anastomotic veins, and superior petrosal sinus. To note, the sphenoparietal sinus (see cavernous sinus) can drain into the transverse sinus. TS drains the superior sagittal, the occipital, and the straight sinuses.

The anatomy of the transverse sinus is highly variable. The left is hypoplastic 39% and aplastic 20% of the time. The right is hypoplastic and aplastic in 6% and 4% of cases, respectively. The two are symmetrical 31% of the time [32].

Sigmoid Sinus

Similar to the transverse sinus, the sigmoid sinus occurs bilaterally. Both sides curve inferomedially in an S-shaped groove within the mastoid process. It then crosses the jugular process of the occipital bone where the sinus migrates forward to end in the superior jugular bulb (part of the internal jugular vein) at the jugular foramen. In the posterior half of the foramen, the pars vascularis, the sigmoid sinus receives blood from the mastoid and condylar emissary veins. This sinus is distinctive because it has a direct connection to the superior petrosal sinus (SPS) (see cavernous sinus) at the transverse sinus junction. In addition, the sigmoid sinus connects to the inferior petrosal sinus (IPS) (see cavernous sinus) to eventually become the internal jugular vein. The sigmoid sinus drains the transverse sinus.

Occipital Sinus

The occipital sinus (OS), one of the smallest dural sinuses, runs cranially and posteriorly along the margin of the falx cerebelli and stops at the confluence of the sinuses. It receives tributaries from the margins of the foramen magnum where it originates.

The OS also receives blood from the veins of the hypoglossal canal, the basilar plexus, the occipital emissary, and the diploic veins. This sinus drains the blood into the confluence of sinuses. In rare occasions, the OS (oblique sinus) will run on one side as opposed to midline and connect with the sigmoid sinus. The OS can be quite large and may even replace one of the sigmoid sinuses. This is especially true in cases of an absent transverse sinus [22, 34]. In most cases, a single occipital sinus is observed, but double occipital sinuses and total absence of the sinus are not uncommon [22, 34].

Cavernous Sinus

The cavernous sinuses (CS) are two sinuses located on either side of the sella turcica. Their course starts anteriorly up to the medial end of the superior orbital fissure and goes posteriorly all the way up to the apex of the petrous bone. Several vital structures run through this sinus, specifically cranial nerves III, IV, VI, V1, and V2 and the internal carotid artery. CS receives blood from the superior and inferior ophthalmic vein, the superficial middle vein, inferior cerebral vein, the sphenoparietal sinus, and the middle meningeal vein. The CS drains into the TS (via the superior petrosal sinus), the internal jugular vein (via the inferior petrosal sinus), the pterygoid plexus (via the emissary veins), and the facial vein (via the superior ophthalmic veins). Communication between the left and right cavernous sinuses is made by the intercavernous sinuses anterior and posterior to the infundibulum of the pituitary gland [23–25].

Both cavernous sinuses drain the orbit and the anterior portion of the cerebral hemispheres.

Superior Petrosal Sinus

The superior petrosal sinus (SPS) is also a paired structure originating within the cavernous sinus, extending along the superior border of the petrous bone and draining into the sigmoid sinus at the transverse sigmoid junction. It receives blood from the vein of vestibular aqueduct, petrosal vein, and the superior veins of the cerebellum. This sinus drains blood from the medulla, pons, superior cerebellum, and internal ear.

Inferior Petrosal Sinus

The IPS is often a plexus of venous channels rather than a true sinus and drains blood from the cavernous sinus to the jugular bulb through the jugular foramen (pars nervosa) or sometimes via a vein passing through the hypoglossal canal to the suboccipital venous plexus. The IPS extends along the inferior border of the petrous bone.

Basilar Venous Plexus

The basilar venous plexus is postulated to arise from a continuation of the cranial part of the anterior internal vertebral venous plexus or arise as its own entity. It is composed of many interconnecting venous channels located between the layers of the dura mater. The plexus has a large number of tributaries such as the IPS, internal vertebral venous plexus, SPS, marginal sinus, veins of the hypoglossal canal, condylar emissary veins, and inferior surface of clivus. This plexus has some anomalies such as two intraosseous connections; one between the plexus itself and the inferior side of the clivus through the basilar canal and the other between the veins of the hypoglossal canal and the condylar emissary veins.

Deep Veins

Internal Cerebral Veins

The internal cerebral veins (ICV) are paired and are the first major deep intracerebral veins. These veins form from the thalamostriate vein, septal vein, and the choroidal vein at the foramen of Monro. The ICV courses posteriorly between the tela choridea of the third ventricle and underneath the splenium. These veins drain the deep cerebral hemisphere and join the basal vein to form the great cerebral vein.

Basal Vein

The basal veins of Rosenthal (BVR), of which there are two, are the third deep intracerebral veins. They lie paramedian and originate on the medial surface of the temporal lobe. The BVR is created by the combination of the inferior striate veins, deep middle cerebral veins, and small anterior cerebral vein. They course posteriorly and medially to pass through the ambient cistern lying lateral to the midbrain before joining with the internal cerebral veins.

Great Cerebral Vein of Galen

The great cerebral vein of Galen (VoG) is the last of the three main deep intracerebral veins. It is a short vein that is formed by the three deep veins of the basal aspect of the brain: the BVRs, ICVs, and some superior cerebellar veins. It is situated in the quadrigeminal cistern, posterior to the brainstem and third ventricle.

The main function of the vein of Galen is to drain blood from the superior cerebellum, interpeduncular fossa, inferior horn of the lateral ventricle, parahippocampal gyrus, corpus callosum, midbrain, and choroid plexuses of the third and lateral ventricles. Its course runs caudally between the splenium and the pineal gland. Subsequently the vein merges with the inferior sagittal sinus to create the straight sinus.

Middle Meningeal Veins

The middle meningeal veins (MMV) follow the course of the middle meningeal artery. MMV passes through the foramen spinosum and the vein empties into the maxillary vein or the pterygoid plexus.

Conclusion

The vascular anatomy of the brain consists of arterial supply and venous drainage. The anterior circulation is supplied by the internal carotid arteries bilaterally. The arterial supply is robust with significant anastomose via the circle of Willis. The vertebral artery enters through the foramen magnum to enter the dura to become the intradural segment (V4). V4 unites bilaterally at the pontomedullary junction to form the basilar artery (BA). BA spans from its origin within the prepontine cistern to the interpeduncular cistern where it bifurcates into terminal branches as the PCAs again into the circle of Willis. The venous system is composed of surface veins and deep veins that drain to the venous sinuses. Ultimately, the venous system flows into the jugular veins.

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