Microsurgical Angioarchitectonics of Deep Brain Structures and Deep Arterial Anastomoses

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■ BACKGROUND: **Surgeries for deep and eloquent cerebral lesions require a detailed knowledge of normal brain anatomy and accurate planning. Important parts of brain anatomy are the cerebral blood supply and collateral circulation system. In addition to well-known cortical and basal (circle of Willis) anastomoses, there is also a deep interarterial anastomotic circle that is not described in the literature.**

■ METHODS: **Twenty brain specimens were studied for deep arterial anastomotic connections between branches of the anterior and posterior choroidal arteries.**

■ RESULTS: **We have marked 3 symmetric zones of deep arterial anastomoses that form an epithalamic circle.**

■ CONCLUSIONS: **Epithalamic anastomoses provide an additional mechanism of blood distribution that may play a role during surgical interventions or stroke.**

INTRODUCTION

Modern equipment has enabled surgeons to operate on cerebral areas that in the past were considered inaccessible, including the thalamencephalon, corpus callosum, pineal gland, and posterior parts of the third ventricle, hippocampal sulcus, caudate nucleus, and other nasal ganglia. Moreover, during the past decade, surgical operations have been performed directly on the brainstem.[1-5]

The expansion of indications to neurosurgical operations has created new problems including the necessity of more detailed knowledge about the microsurgical angioarchitectonics of the aforementioned structures and has defined the “borders” of research work in the present anatomic investigation.

Surgical operations on deep and eloquent cerebral structures require wise planning and adequate surgical approaches. Precise anatomic landmarks should help to identify arterial segments and branches in narrow operative corridors at significant depths. Safer and less invasive surgeries focused on quality of life have become an implicit goal for modern neurosurgeons. Normal arterial anatomy and collateral blood supply are 2 important elements defining the quality of surgery and its consequences.

There is a series of anatomic articles published in the past 2 decades with special attention to deep structures and the microsurgical anatomy of the arterial supply.[6-12] Most studies offer a detailed and comprehensive morphometric approach to brain anatomy. Deep-seated arterial anastomosis, although reported by many, still lacks a definitive description. Thus we have considered this anatomic issue clinically important and far from complete.

We use the term “microsurgical angioarchitectonics” to emphasize the anatomic nature of our study. Two main considerations determining our point of view on anatomic investigation endpoints should be mentioned here. First, all anatomic studies must be supported by surgical practice, and their results have direct practical application. Second, an anatomic study should be object oriented, focusing on certain surgical procedures or lesions. Any neurosurgical intervention requires detailed knowledge of arterial and venous brain anatomy to prevent complications and improve overall results of treatment.

MATERIALS AND METHODS

Twenty cadaver brain specimens were used for anatomic studies. In all cases, brains were extracted and vessels were injected within 24 hours after death associated with a noncerebral cause. The age

Key words
- Deep arterial anastomoses
- Epithalamic arterial circle
- Normal brain anatomy
- Neurosurgery

Abbreviations and Acronyms
AChA: Anterior choroidal artery
HA: Hippocampal artery
ICA: Internal carotid artery
PCA: Posterior cerebral artery
PComA: Posterior communicating artery
PLChA: Posterior lateral choroid artery
PMChA: Posterior medial choroid artery
SCA: Superior cerebellar artery

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of cadavers varied from 12–81 years. The arteries and veins were injected with red and black fine-dispersed latex with particle diameters of 1000–1200 nm.

The latex injections were performed under visual control through both vertebral arteries and both internal carotid arteries (ICAs). In several cases, unilateral internal carotid artery (ICA) and posterior cerebral artery (PCA) selective catheterization with injection of latex was performed for better identification of deep-seated arterial anastomoses. This technique facilitates visualization of deep-seated small arteries and their further dissection. Latex polymerization usually requires 30–40 minutes. Brain fixation was started with 3% formalin solution followed by 10% solution. The brain was placed in a gauze sling for 7–10 days; then, 10% formalin solution was injected into the temporal horn of the lateral ventricle. Dissection of cerebral vessels was performed using a microsurgical toolkit and operation microscope OPMI-6 (Germany). Specimens were photographed with the Zeiss Ikon camera using convertible transparency film IT-18 and a black-and-white film, MIKRAT-200.

RESULTS

Microsurgical Anatomy of Anterior Choroidal Artery

The system of choroidal arteries (anterior and posterior lateral choroidal arteries in particular) plays a critical role in the blood supply of deep cerebral structures. The anterior choroidal artery (AChA) is the third branch of the supraclinoid ICA found at the posterior aspect distal to the posterior communicating artery (PComA) in 100% of specimens. The diameter of the AChA varied from 0.5–1.2 mm. The AChA was divided into 2 trunks in 10 cases (25%). The length of the AChA from the origin to the plexus point at the temporal horn varied from 2–3 cm (mean 2.7 cm). The AChA lies laterally and posteriorly to the temporal horn and is usually located below the optic tract and basal vein of Rosenthal. On its way, the AChA crosses the optic tract and vein of Rosenthal, making 1 or 2 curves.

Our anatomic investigation demonstrated that in all 40 specimens, the AChA perforants to the internal capsule originated from the anterior one third (Figure 1). The AChA had no branches in middle and posterior one third except for a few branches to the optic tract and adjacent structures of the temporal cortex (Figure 2). Thus it is safer to occlude the AChA close to the plexus point (end of cisternal segment) or inside the ventricle before the AChA joins this plexus.

We have marked 3 anastomotic zones between the anterior and posterior choroidal arteries' supply, to form a deep circle (see Figure 1). The first one is formed with branches of the AChA and posterior lateral choroid artery (PLChA) and found near the lateral geniculate body at the distal portion of the AChA cisternal segment (see Figure 2).

The hippocampal blood supply is highly variable. The hippocampal arteries (HAs) (3–8 trunks) typically are divided into 3 groups (anterior, middle, and posterior HAs) with origins at the PCA, AChoA, anterior and inferior temporal arteries, and splenial artery. The anastomoses were identified at the entry level of the intraventricular segment between the PLChA and AChA branch in 9 specimens (22.5%). The hippocampal artery (HA) originating from the postcommunicant (P_2) segment of the PCA was found in

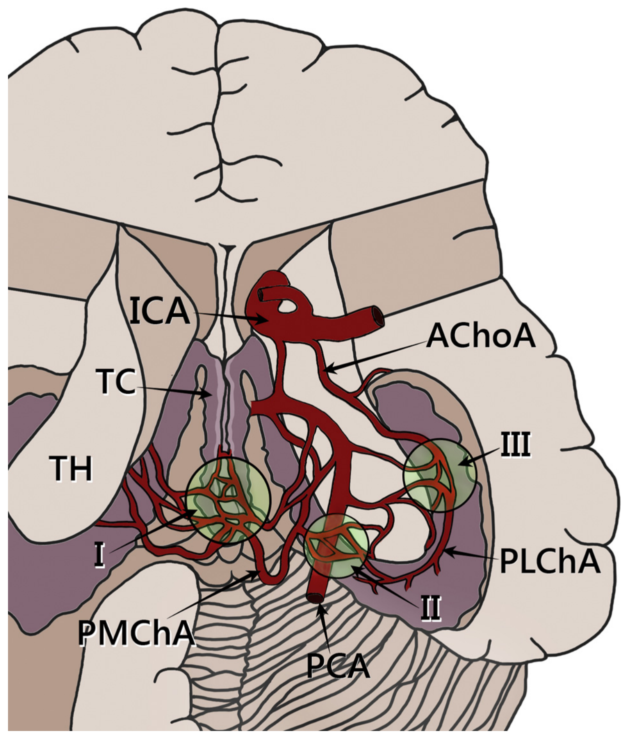

Figure 1. Epithalamic anastomoses circle (scheme): 3 zones of deep anastomoses formed by branches of the anterior choroidal artery (AChoA)–posterior lateral choroid artery (PLChA) (Zone 1), the posterior lateral choroid artery (PLChA)–posterior medial choroid artery (PMChA) (Zone 2), and between the left and right branches of the posterior lateral choroid artery/posterior medial choroid artery (Zone 3). ICA, internal carotid artery; PCA, posterior cerebral artery; TC, tela choroidea; TH, thalamus.

12 specimens (30%). The HAs originated from the trunk of the posterior medial choroid artery (PMChA) in 4 cases (10%). The HA diameter varied from 0.2–1 mm (mean 0.8 mm). The HA supplied the middle-posterior parts of the hippocampus and dentate gyrus in all 40 specimens. The interarterial anastomoses between branches of the HA and AChA were found in 11 specimens (27.5%). These anastomoses had a reticular or multicanalicular structure.

According to our study, the length of the inferior lateral choroid plexus varies from 3.5–6 cm (mean 4.5 cm). The inferior lateral choroid plexus lies inside the temporal horn, and its posterior part projects dorsally, ending at the level of the posterior one third of the caudate nucleus. The PLChA and its branches contribute supply to the superior lateral choroid plexus, building a combined blood supply zone. This second arterial anastomotic zone is located in the thalamic pulvinar at the junction of both parts of the lateral choroid plexus. These anastomoses were found to be solitary, double, or multiple to form an arterial network (Figure 3). The second anastomotic zone was reticular in 18 specimens (45%). The AChA could be visualized up to its entrance to the temporal horn with a pterional approach through the sylvian fissure or with a subtemporal approach.

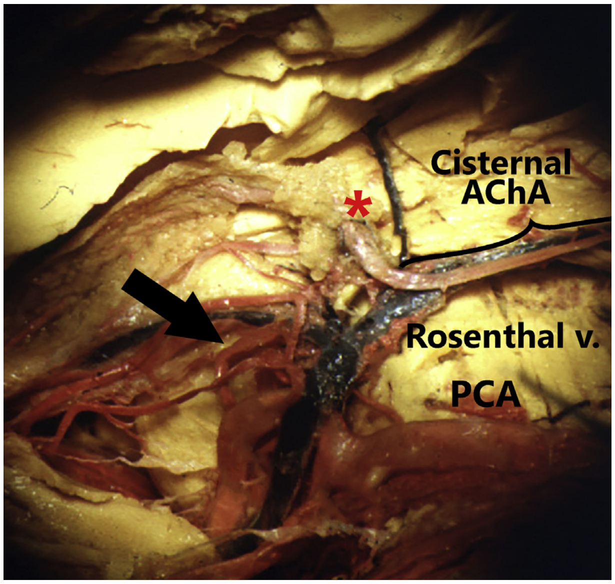

Figure 2. The first zone of deep arterial anastomoses. Right temporal horn, basal view. The anterior choroidal artery (ACha) (cisternal segment) to the plexus point (*star*) is dissected. Anastomoses between the anterior choroidal artery and posterior lateral choroid artery (PCA) are marked with a *black arrow*.

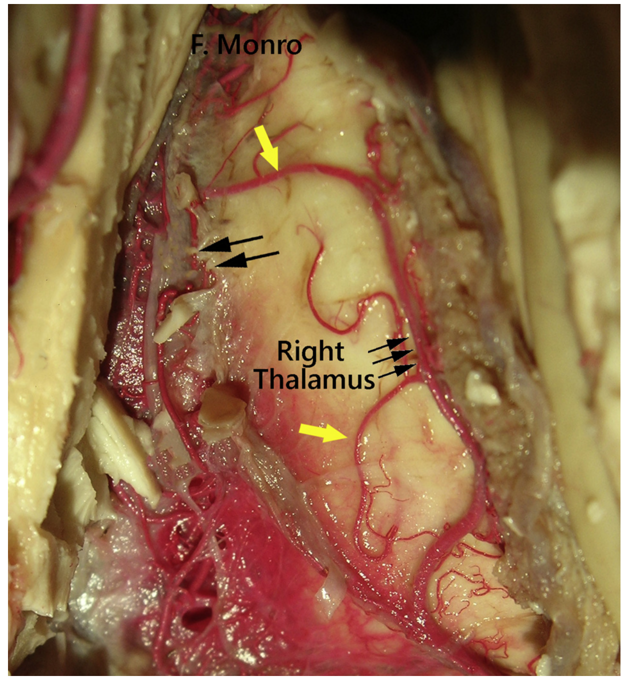

Figure 3. The second zone of deep arterial anastomoses. The right lateral ventricle and thalamus are dissected (view from above). Branches of the right posterior medial choroid artery (*double black arrows*) anastomose with branches of the right posterior lateral choroid artery (*triple black arrows*). The anastomoses are marked with *yellow arrows*.

The main feeders of the lateral choroid plexus are branches of the AChA and PLChA. We have found that, first, an intraventricular segment of the AChA branches to the internal capsule, and that, in turn, branches of the distal one third of the AChA supply only the optic tract, basal cortex of the temporal lobe, and the lateral geniculate bodies. Second, we found anastomoses between the AChA and PLChA close to the lateral geniculate bodies and between the PLChA and PMChA on the basal and ventral surfaces of the pulvinar. Therefore if an AChA occlusion is required, it should be done at the level of its intraventricular segment.[9] Furthermore, we were able to follow the course of the AChA branches to the foramen of Monroe in 21 specimens (53%). In the rest, the AChA has a dispersed type of structure. In any type, the AChA distal segment has branches supplying the thalamus and posterior parts of the caudate nucleus.

The cisternal segment of the AChA ends entering the temporal horn of the lateral ventricle. Although the length of this segment may vary, there are strong data that the trunk of the AChA does not pass through the ambient cistern. This fact may play a role in surgeries when one identifies vessels within the ambient cistern.

All branches in the ambient cistern come from the posterior choroid arteries, long circumflex branches of the PCA, or quadrigeminal branches. These arteries supplying the basal ganglia also give branches to the brainstem. The cortical branches originating from the PCA and supplying adjacent regions of the cerebral cortex, mediobasal areas of the temporal lobe, the posterior one third of the hippocampal gyrus, and the occipital lobe may be sacrificed without severe neurologic sequelae. The ambient cistern with its arteries is depicted in Figure 4.

Microsurgical Anatomy of Posterior Medial Choroid Artery

The PMChA originates from the PCA P2 segment as a single branch (62.5%) or multiple branches (37.5%). The diameter of the PMChA trunk(s) varies from 0.5—0.9 mm. The first segment of the PMChA repeats the course of the PCA, going parallel to the PCA, then the quadrigeminal artery, and the long circumflex rami of the PCA (Figure 5).

The PMChA trunk is angled at the superior-lateral margin of the quadrigeminal plate, and it enters the cavity of the third ventricle under the corpus callosum and proceeds over the superior-internal surface of the ventricle (roof of the third ventricle) to the foramen of Monroe. The PMChA forms anastomoses with the ipsilateral PLChA and branches of the contralateral PMChA (third deep arterial anastomotic zone). This zone is located in the tela choroidea of the third ventricle and the caudate nucleus. This way, the third arterial anastomotic zone includes anastomoses not only between the ipsilateral, but also the contralateral, PMChA, and PLChA (Figure 6).

Branches from the PMChA supply cerebral peduncles, the pineal gland, and the anterior colliculi. At the quadrigeminal plate branches of the PCA (by Rhoton classification—long circumflex arteries, distal segments of PCA trunks of the first division) anastomose with branches of the superior cerebellar artery (SCA).[9] This anastomotic network is similar to the one formed by the branches of the SCA and quadrigeminal artery that, in most

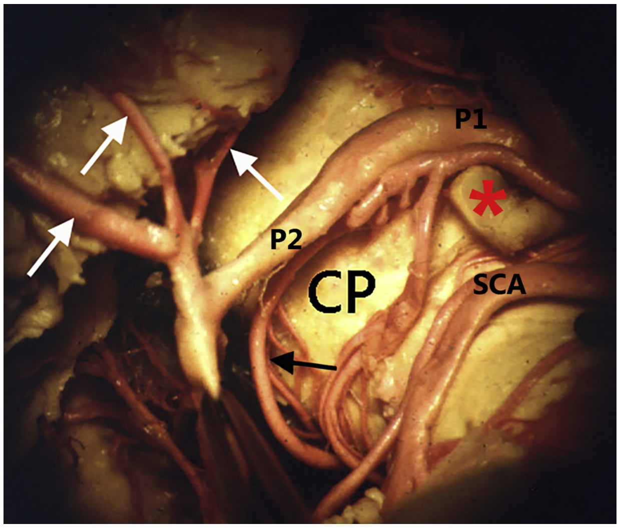

Figure 4. The upper brainstem and ambient cistern dissected, anterolateral view. The right cerebral peduncle, nerve III (cut, marked with *red star*), and P1-P2 segments of the right posterior cerebral artery (PCA) and right superior cerebellar artery (SCA) are depicted. The right posterior medial choroid artery is marked with a *black arrow;* the temporal branches of the right PCA are marked with *white arrows.*

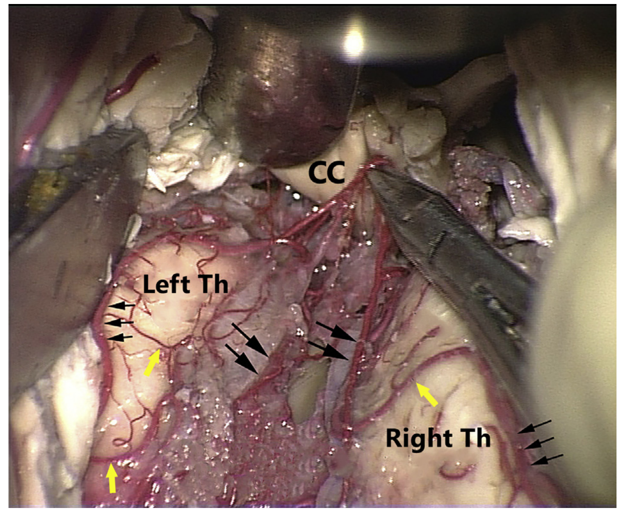

Figure 6. The third zone of the deep arterial anastomoses. The tela choroidea and both thalamus (Th) bodies are visualized from above. The branches of the left and right posterior medial choroid artery (*double black arrows*) and posterior lateral choroid artery (*triple black arrows*) anastomose within each side and left to right via the tela choroidea (*yellow arrows*). CC, corpus collosum.

cases, originate from the precommunicant segment of the PCA (Figure 7). The central rami of the PMChA supply the pulvinar and thalamus to form anastomoses with the PLChA in the pulvinar region mentioned previously (second deep interarterial anastomotic zone). The structure of the described anastomoses is difficult to classify because they are presented by vascular networks of different intensity. The diameter of the anastomotic rami varies from 0.1–0.3 mm.

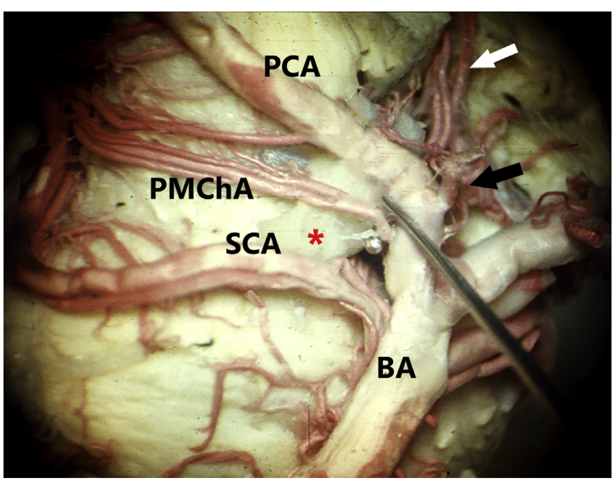

Figure 5. The upper brainstem and basilar artery tip, anterior view. The right superior cerebellar artery, nerve III (cut, marked with *red star*), right posterior artery, and posterior medial choroid artery are presented. The posterior communicating artery (*black arrow*) and thalamoperforating arteries (*white arrow*) are visualized. PCA, posterior cerebral artery; SCA, superior cerebellar artery.

Selective vascularization by each branch of the PMChA was observed when the PMChA originated with multiple branches (15 cases). Some branches were followed to supply the choroid plexus of the third ventricle; the others supplied the pulvinar and medial surface of the thalamus. The identification of these trunks at the level of their cisternal segments is extremely difficult.

From a surgical point of view, it is important to remember that the intraventricular segment of the PMChA has no direct branches to the brainstem. Occlusion at this level seems safe, whereas occlusion at the cisternal (ambient and quardigeminal) segment should be avoided.

Microsurgical Anatomy of Posterior Lateral Choroid Artery

The posterior lateral choroid artery (PLChA) was identified in 34 specimens (85%) as a single trunk originating from the PCA at the level of the cerebral peduncle; in 6 cases (15%), it was a group of small arteries. The diameter of the main trunk varied from 0.4–0.8 mm. The PLChA repeats the course of the cisternal (P3) segment of the PCA within the ambient cistern, curved toward the anterior and upward at the border between the quadrigeminal and ambient cisterns. Further distally it passed below the cerebral peduncle on the superior-lateral surface of the thalamus, giving branches to the posterior-lateral surface of the thalamus and choroid plexus of the lateral ventricle. The arteries supplying the caudate nucleus originated from the PLChA distally. Distally, the

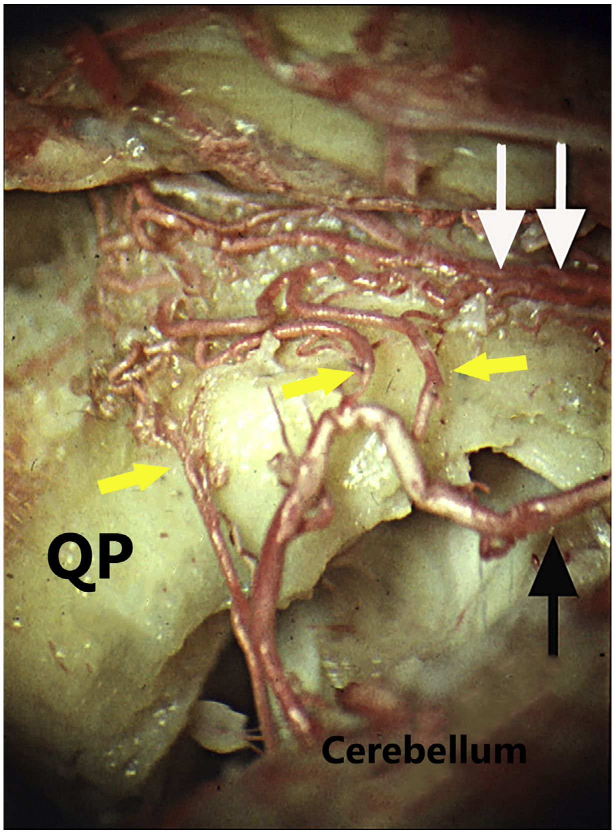

Figure 7. The quadrigeminal plate, posterior lateral view, right side. The right quadrigeminal artery and branch of superior cerebellar artery (SCA) (*black arrow*) anastomose with branches of the long circumflex artery of the posterior cerebral artery (PCA) (*white arrows*). Anastomoses are marked with *yellow arrows*. QP, quadrigeminal plate.

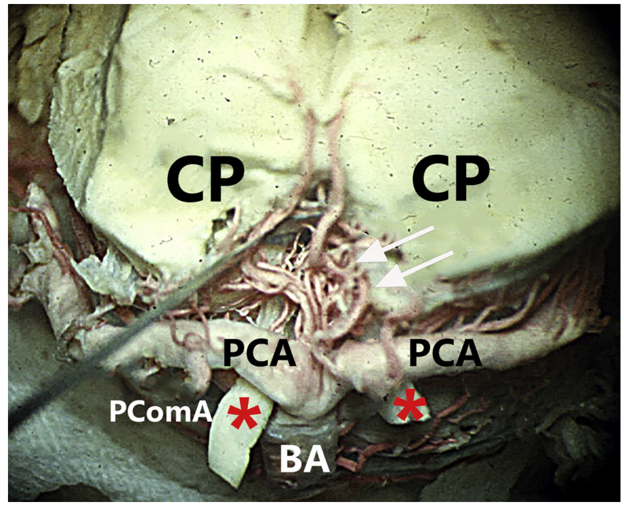

Figure 8. The brainstem and cerebral peduncles (CP), frontal view from above. The basilar artery (BA), both posterior cerebral arteries (PCAs), posterior communicating artery (PComA), and third nerves (cut, marked with *red stars*) are presented. The thalamoperforating arteries are marked with *white arrows*.

PLChA branches passed through the foramen of Monroe to anastomose with the terminal branches of the PMChA (third zone of the deep arterial anastomoses). The most prominent network of the anastomoses between the PLChA and the PMChA branches was found at the pulvinar and the thalamus (second zone of the deep arterial anastomoses) (Figure 3). Three to four branches from the PLChA pass under the fornix and form anastomoses with branches of the PMChA. Thus we may conclude that the AChA, PMChA, and PLChA branches form a deep-seated system of cerebral arterial anastomoses connecting distribution areas of the ICA and PCA both ipsilaterally and contralaterally.

Thalamoperforating Arteries

These arteries are ganglionic branches of the PCA that supply subcortical structures, the brainstem, and the internal capsule. They may have a common stem of origin (50% in our series) or originate as individual vessels. The number of perforating arteries was variable (2–7), with a mean of 4 arteries on each side. Identification of the thalamoperforating arteries is quite difficult. In our study, these have always originated from the dorsal wall of the precommunicant segment of the PCA with trunks (1–2 on each side) and are larger than other perforating arteries (0.5–1.8 mm, mean 0.9 mm). The thalamoperforating arteries pierce the posterior perforated substance (Figure 8).

It is worth mentioning that the thalamoperforating arteries do not form anastomoses with adjacent arteries of the brainstem, which is what emphasizes their ultimate functional importance during surgery.

DISCUSSION

Anastomoses between the anterior choroidal and posterior choroidal artery have been described before in anatomic studies by different authors.[9,13] In an angiography-based study, Krayenbühl and Yaşargil[14] were the first to define an anastomosis between branches of the anterior and posterior choroidal arteries as "circulus arteriosus intracerebralis." The incidence and contributing arteries may vary. Hussein et al[15,16] reported finding anastomoses between choroidal arteries in 32% and Carpenter in 93%; in our study, we have found anastomoses in all 20 specimens.

Our anatomic study supports the conclusions that besides the well-known cortical anastomosis (circle of Willis), there is a deep-seated interarterial anastomotic circle. We have marked out 3 zones of deep symmetric arterial anastomoses that form an epithalamic circle. This epithalamic circle provides an additional mechanism of blood distribution from both the carotid and vertebra-basilar system. Obviously, it is quite variable from the point of anatomy, and its hemodynamic role is yet to be determined. No accurate description or structure was previously presented. In 1969, Shmidt[17] described a 4-level collateral cerebral blood circulation dividing anastomoses into extracranial, basal (circle of Willis), cortical, and deep-seated.

Generally, the AChA has anastomoses with branches of the posterior choroidal arteries and the PCA, which may compensate blood flow in the anterior but not posterior limb of the internal capsule if the AChA is compromised. AChA occlusion leads to the classical syndrome with a triad of symptoms: hemiparesis, hemianesthesia, and hemianopia. AChoA infarction is less frequent in the thalamus, midbrain, temporal lobe, and lateral geniculate body territories as they are covered with collateral flow. Hemisensory loss is usually transient, and visual defects may include homonymous upper-quadrant anopia, hemianopia, or upper- and lower-quadrant sector anopsia.[18] The degree of neurologic deficit in AChoA infarct is individual and may vary from transient symptoms to severe brachiofacial syndrome. The most common etiology of AChA infarct is small-vessel occlusive disease, more likely to be found in hypertensive and diabetic patients, but cardiac embolism also plays a role. The AChA is at risk during surgeries for ICA aneurysms, especially large and giant ones, independent of the type of intervention. AChoA aneurysms are rare (2%–5%) with high postoperative ischemic complications (5%–50%) after clipping.[19] Flow-diverters have gained increasing popularity among interventional surgeons to occlude complex, large, and broad-neck ICA aneurysms. Although stents are frequently placed over the branching vessels adjacent to aneurysms, follow-up studies show that occlusions (3%–15.8%) in most cases remain silent.[20,21]

The posterior perforating arteries include arteries from the basilar tip (P1 segment) and PComA, which enter at the posterior perforated substance, interpeduncular fossa, and from the medial side of the cerebral peduncle. These arteries bring supply to the posterior thalamus, hypothalamus, substantia nigra, red nucleus, and reticular formation of the midbrain. The first description belongs to Duret and Heubner.[22,23] Compromise to the posterior thalamoperforating arteries may lead to various neurologic deficits including ataxia, hemiplegia, and "rubral" tremor with ipsilateral III nerve paresis. In 8%–11.5% of cases the thalamoperforating arteries arise from a single unilateral trunk (artery of Percheron), which, if occluded, leads to a bilateral medial thalamic infarct.[24]

The thalamogeniculate perforating arteries (P2 segment) usually arise in the crural or ambient cisterns (80%) or the quadrigeminal cistern (20%) and further penetrate the medial geniculate body, pulvinar thalami, superior colliculus, or lateral geniculate body. Milisavljevic et al[25] have found P2 perforating arteries to anastomose with branches of the PMChA (33.33%) or mesencephalothalamic arteries (26.67%). These findings support the idea that the perforating arteries are individual and variable anatomic structures.

CONCLUSION

Study of anterior and posterior choroidal arteries anatomy is of paramount importance to practicing neurosurgeons and neurologists. Microsurgical anatomy of deep anastomoses is helpful in clinical diagnostics and operative planning to improve outcomes of treatment. Further study to define the role of the deep-seated anastomotic circle is necessary.

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