THE CIRCLE OF WILLIS REVISITED: ITS ANATOMY AND FUNCTION

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THE CIRCLE OF WILLIS REVISITED: ITS ANATOMY AND FUNCTION (Abstract): Circle of Willis (CoW) is located at the base of the brain, around the optic chiasm and other structures of the interpeduncular fossa. There are other studies in which the „circle of Willis” is not considered a circle, but an arterial polygon with a variable number of sides (from six to ten) depending on the author. Circle of Willis is composed of an anterior arch, which derived from the internal carotid artery and is made of the two paired anterior cerebral arteries and anterior communicating artery, and a posterior arch, made of posterior cerebral artery originating in the vertebrobasilar system, and the two paired posterior communicating arteries, having their origin in the internal carotid system. In this paper we present a comprehensive review of the data regarding the anatomical course and morphological aspects of each of the arteries constituting the circle of Willis, along with their anatomical variants and the pathology that emerged from these anomalies, pointing out their significance for the clinicians. Key-words: CIRCLE OF WILLIS, INTERNAL CAROTID SYSTEM, VERTEBROBASILLARY SYSTEM, PERFORATING ARTERIES

INTRODUCTION

Circle of Willis (CoW) is located at the base of the brain, around the optic chiasm and other structures of the interpeduncular fossa. It is an arterial anastomosis that provide constant oxygenated blood supply to the brain. It was considered to be an arterial circle and was named circulus arteriosus cerebri.

IS CIRCLE OF WILLIS A CIRCLE OR A POLYGON?

CoW is not actually a circle, but a polygon-shaped anastomotic arterial channel (Figure 1), described by different authors as being hexagonal (2), heptagonal (3), and even nonagonal by others (4), so that the name „polygon” of Willis seems to fit better than that of „circle” of Willis. For these reasons, the name of this structure is made interchangeable, either as circle of Willis or as polygon of Willis. Whatever it is called, it is one of the most famous eponymous structures in human anatomy.

In the English literature this anatomical structure is often called the „circle” or the arterial „ring” that connects both halves of the brain anterior circulation to each other and to the vertebro-basilar system (5, 6).

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depending on the author.

Many authors describe the circle of Willis as a heptagon formed as follows (7):
• anterior side made of the anterior communicating artery (ACoA);
• antero-lateral sides represented by two paired anterior cerebral arteries (ACAs), left and right;
• postero-lateral sides made by two paired posterior communicating arteries (ACoP), left and right;
• posterior side represented by two paired posterior cerebral arteries (ACP), left and right.

Other authors (5) consider circulus arteriosus cerebri to be in fact an octagon, composed as follows:
• the supraclinoid segments of right and left internal carotid arteries (ICAs) represent two of its sides;
• horizontal, precommunicating (A1) right and left segments of the anterior cerebral arteries (ACA) made another two sides;
• anterior communicating artery (ACoA) realises the anterior side;
• right and left posterior communicating arteries (PCoAs) made other two posterior sides;
• the tip of the basilar artery (BA) realises its posterior side.

There are also researchers (6) who consider that circle of Willis is in fact a nonagon or a structure with nine sides, because they present it as consisting of the following sides:
• anterior: anterior communicating artery (ACoA);
• antero-lateral: right and left anterior cerebral arteries (ACAs);
• lateral: the proximal segments of the right and left internal carotid arteries (ICAs);
• posterolateral: right and left posterior communicating arteries (PCoAs);
• posterior: the proximal segments of right and left posterior cerebral arteries (PCAs).

Some other authors (8) consider that a complete CoW consists of ten arterial sides, as follows: two internal carotid arteries (ICAs), two anterior cerebral arteries (ACAs), one anterior communicating artery (ACoA), two posterior communicating arteries (PCoAs), two posterior cerebral arteries (PCAs) and the basilar artery (BA).

Fig. 1. Anatomy of the circle of Willis at the base of the brain (1) (public domain).
In literature, there is also the concept that a complete *circulus arteriosus cerebri* consists of ten arterial sides (8), as follows: two paired internal carotid arteries (ICAs), two paired anterior cerebral arteries (ACAs), one anterior communicating artery (ACoA), two paired posterior communicating arteries (PCoAs), two paired posterior cerebral arteries (PCAs) and the basilar artery (BA).

**THE STRUCTURE OF THE CIRCLE OF WILLIS**

With the exception of the two paired PCAs, which are part of the vertebro-basilar system, all the other branches of the circle of Willis (CoW) belong to the internal carotid system (7). It is considered that circle of Willis is made up of two parts: an anterior one and a posterior one.

**The anterior arch of the circle of Willis**

The anterior part of the circle of Willis derived from the internal carotid artery (ICA), a terminal branch of the common carotid artery (CCA). It crosses the carotid canal at the base of the skull and enters the middle cranial fossa (9).

In the subarachnoid space, at the base of the brain, ICA engages under the optic nerve and then goes laterally and upward, immediately outside the optic chiasm, reaching the anterior perforated space where it ends by bifurcating into the anterior cerebral artery (ACA) and middle cerebral artery (MCA).

From its subarachnoid segment, the internal carotid artery (ICA) sends four important collateral branches: the superior pituitary artery, the ophthalmic artery, the posterior communicating artery, and the anterior choroidal artery.

**Structure and function of the anterior cerebral artery**

The anterior cerebral artery (ACA) is the medial branch of the ICA bifurcation, being the smaller terminal artery when it is compared with the middle cerebral artery, the second terminal branch. Anatomically, angiographically and surgically, it has three segments:

- **A1 segment**, which extends from the bifurcation of the ICA in the medial and superior direction and then it unites with the ACoA in the interhemispheric fissure (Fig. 2). It goes above the optic chiasm and optic nerves and below the anterior perforated substance (10).
- **A2 segment**, which enters the interhemispheric fissure, embracing the knee of the corpus callosum, before which it passes. At the junction of these two segments (A1 and A2), right and left ACAs joined together by a small transverse vessel, named anterior communicating artery (ACoA).
- **A3 segment** is the part where the ACA courses on the medial surface of the cerebral hemisphere, over the superior surface of the corpus callosum. At this level it is called the pericallosal artery, which ends by irrigating the medial surface of the parietal lobe and the precuneus (7).

ACA can present some anatomical variants, such as: hypoplasia, fenestration, duplication and longer length of the vessel with the appearance of a sinuous trajectory, thus impairing the blood flow and as such leading to stroke or aneurysm formation (11). Also, ACoAs can present some anatomical variations, such as absence, duplication and hypoplasia of the vessel (11). These anatomical variants can also lead to aneurysm formation (12), often with fatal consequences.

**Structure and function of the anterior communicating artery**

The anterior communicating artery (ACoA) unites the two anterior cerebral arteries at the junction of their A1 segment with A2 segment.

The length of ACoA ranged from 0 to 9.5 mm (mean 3.34 mm) and its diameter can vary from 0.2 to 3.9 mm (mean 1.22 mm) (13).

ACoA presents perforating branches, whose number varies from 0 to 5, supplying the corpus callosum, the anterior part of hypothalamus, the optic chiasm, anterior perforated substance, prefrontal cortex and cingulate gyrus, and thus can be classified into the following: subcallosal (the most important), hypothalamic, and chiasmatic branches, according to their vascular territories (7, 13, 14).

ACoA can present many types of variations, closely related to its embryology and development. Plexiform and fenestration are the most frequent anomalies, but some other anatomical variants can appeared, such as duplication, fusion, string, dimple, median artery of the corpus callosum and azygous anterior cerebral artery (14). These anatomical variants should be taken into consideration especially by neurosurgeons as they can lead to the formation of...
aneurysms, as ACoA is the preferred location (75%) of intracranial arterial ruptured or unruptured aneurysms (15).

The posterior arch of the circle of Willis

Structure and function of the posterior communicating artery

Posterior communicating artery is a small branch of the internal carotid artery, but it represents a significant importance as it assures the communication between the internal carotid arterial system and the vertebro-basilar arterial system (16).

There are two posterior communicating artery (PCoA), one at the right and one at the left (Figure 2). Each of these two arteries contributes to the formation of CoW as each of them directs posteriorly and anastomoses with the proximal segment (P1) of the ipsilateral PCA. Bordering the hypothalamus on its lateral side, PCoA forms the lateral sides of the CoW.

The posterior communicating artery (PCoA) is the origin of several (5 to 8) arterial perforating branches that supply the optic chiasm, optic tract, mamillary bodies, the anterior third of the thalamus, the subthalamus and the lateral hypothalamus. The location of these perforating branches should be known by neurosurgeons especially during interventions for aneurysms, as they supply important structures of the brain (17).

It is worth to mention that at the origin of PCoA from ICA there is an almost constant dilatation called infundibulum, which must be taken into account to distinguish it from an aneurysm that occurs predominantly in the same place (7).

PCoAs mainly present hypoplastic variations (<1 mm in diameter), uni- or bilaterally, and this anatomical anomaly is correlated with abnormal hemodynamic stress leading to ischemic stroke especially in case of an occlusion of one or both of the internal carotid arteries. In rare cases, PCoA can run posterolaterally and ends into an unnamed extra loop originating in the ipsilateral Posterior Cerebral Artery (PCA) and thus forming an extrasegment in the posterior boundary of CoW (12).

Structure and function of the posterior cerebral artery

There are two posterior cerebral arteries (PCA), right and left, which mainly arise (70% of cases) from the basilar artery (BA) (Figure 2), at its bifurcation site, from the posterior communicating arteries (in 20% of cases), and a mix of the two for the remaining 10% of cases (18). The basilar artery (BA) forms from the convergence of the two vertebral arteries (VAs) at the caudal edge of the pons (Figure 2).

It sits in the middle of the ventral face of the pons and ends normally near the ponto-mesencephalic junction by dividing into two lateral branches, the left and right posterior cerebral artery (PCA), which are also its terminal branches. At a variable distance from their origin, each PCA joins with the ipsilateral PCoA to close the circle of Willis (7). In the irrigation of the cerebral hemisphere, the PCA territory completes that of the anterior cerebral artery (ACA) and of the middle cerebral artery (MCA).

Anatomically and angiographically, PCA presents five segments (18):

- An initial segment, also called pre-communicating segment or P1 segment, is located in the interpeduncular cistern of the subarachnoid space, on the ventral surface of the cerebral peduncle. The right and left P1 segments have a lateral direction on the surface of the upper pons and the midbrain, being called for this reason the midbrain segments. They are also located immediately above the oculomotor and trochlear nerves. P1 segment length is measured up to the site of implantation of PCoA in PCA. Its average length is 6.6 mm. When the fetal variant is present, the length of the vessel is 8.6 mm (9). This segment gives off small paramedian arteries that supply the rostral midbrain and thalamo-perforating arteries which supply part of the thalamus. It may also give off the artery of Percheron, which is a rare anatomic variant that can supply the thalamus and midbrain bilaterally (18);
- The P2 segment begins at the site of implantation of the posterior communicating artery (PCoA) and curves around the ambient cistern of the midbrain, and courses above the tentorium cerebelli. This segment is the origin of the posterior choroidal artery, but it also gives rise to peduncular perforating arteries that supply the lateral midbrain as well as thalamogeniculate arteries that supply the ventrolateral portion of the thalamus (18);
The P3 segment of the PCA refers to the part of the artery that runs through the quadrigeminal cistern. This segment commonly gives off anterior and posterior inferior temporal arteries (18);

The P4 segment is the last segment of the PCA as it ends in the calcarine sulcus. This segment gives rise to the parieto-occipital branches and the calcarine artery, which supplies areas bordering the calcarine sulcus and the medial surface of the occipital lobe (18);

The P5 segment represents the terminal branches of PCA, i.e. the parieto-occipital and the calcarine arteries (18). Each of the two PCAs is anastomosed with the ipsilateral MCA and ICA via PCoA also on the same side, thus representing one of the PW sides.

The functional role of each PCA is to ensure oxygenated blood irrigation of the two occipital lobes, the primary visual processing center of the human brain, so that damage to any of these two vessels, can affect vision. For example,
even a transient ischemic attack due to a small embolus manifests as a transient monocular vision loss (19).

Numerous anatomical variants of this artery have been reported. One of them is the fetal posterior cerebral artery (f-PCA) was correlated with ischemic stroke, either ipsilateral, or controlateral (19).

**Small perforating arterial branches of the circle of Willis**

CoW branches into several small perforating (central) arteries, which pass into the brain through the anterior and posterior perforated substances and provide oxygenated blood to structures on the ventral surface of the brain such as the optic chiasm, pituitary gland, mammillary bodies and pineal gland, but also to the deep structures of the brain, including the internal capsule, basal ganglia and diencephalon.

These penetrating branches of the CoW are as follows (7, 10):

1. Antero-medial branches, which derive from ACoA and the first segment (A1) of ACA and enter the anterior perforated substance. These small arteries are distributed to the preoptic and supraoptic region of the anterior hypothalamus.

2. Two paired antero-lateral branches are distributed to the striated body and the internal capsule. These small vessels derive from the medial striatal branches of the ACAs and the lateral striatal branches of the MCAs.

3. Postero-medial branches derived from PCoA and PCA and are represented by anterior thalamo-perforators which supply the thalamus, brainstem and the internal capsule.

4. Two paired postero-lateral branches, which are distributed to the caudal part of the thalamus, geniculate bodies and lateral thalamic nuclei and derive from the PCAs.

**FUNCTIONS OF THE CIRCLE OF WILLIS**

Even from the moment of description of the anatomy of the arterial circle at the base of the brain (20), Thomas Willis also appreciated its compensatory function of redistribution of blood flow in the case of stenosis or occlusion events of one of the arteries that irrigates the brain, i.e. ICAs or BA.

The ideal arterial brain polygon, presenting all its sides and being well calibrated, has a remarkable compensatory capacity, allowing a normal survival even in case of obstruction of three of the four main arteries (7).

Circle of Willis (CoW) distributes and balances blood flow to any part of the two cerebral hemispheres in pathological condition (i.e. stenosis or occlusion), but CoW has no function under physiological conditions, given the equality of pressures in the two arterial systems. As such, a new theory regarding the function of circle of Willis has emerged in the last years. Vrselja et al. (21) considered that from the evolutionary point of view, the compensatory function of the CoW is incorrect, since the role of CoW appears only in pathologic conditions of the older age. Moreover, the communicating arteries are too small or hypoplastic in majority of the population, hence ineffective for blood transfer. The communicating arteries of CoW probably serve as a passive energy (pressure) dissipating system: they transfer pressure without considerable blood flow from the high pressure end to the low pressure end, the latter being other arterial components of CoW, where pulse wave and blood flow arrive asynchronously.

**CONCLUSION**

The circle of Willis is an anatomical name for arteries found at the base of the human brain, which are assembled in a circular or rather polygonal configuration. It is an anastomosis of the carotid arteries and the basilar artery. The two paired anterior communicating artery, the two paired anterior cerebral arteries, the two paired internal carotid arteries, the two paired posterior communicating arteries, the two paired posterior cerebral arteries and the basilar artery contribute to the formation of the circle of Willis. All these arteries, by their way of connection, allow the distribution of blood from the internal carotid artery or the basilar artery to any part of both cerebral hemispheres. The branches of these arteries that detach from the circle also feed the brain. The important function of the Willis circle is redistribution of cerebral blood flow in cases of reduced upstream flow. Moreover, it can be added that the numerous anatomical variants give its compensatory performance a random character, therefore its functional value is unpredictable, depending on its mode of formation (normal or defective), as well as of the caliber of the vessels that make it up.
REFERENCES


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