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ANATOMICAL AND CLINICAL FEATURES OF THE CIRCLE OF WILLIS: VARIATIONS AND THEIR ROLE IN CEREBROVASCULAR DISORDERS



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Abstract

The Circle of Willis is a major arterial anastomotic network located at the base of the brain and plays an essential role in maintaining cerebral perfusion when blood flow through one of the principal cerebral arteries is reduced or interrupted. Although the classical configuration of the Circle of Willis is frequently described in anatomical textbooks, complete and symmetrical anatomy is not present in all individuals. Variations such as hypoplasia, aplasia, duplication, fenestration, fetal-type posterior cerebral artery, asymmetry, and incomplete arterial connections are common and may influence cerebral collateral circulation. The aim of this study was to analyze the anatomical variants of the Circle of Willis and evaluate their clinical significance in cerebrovascular disorders, including ischemic stroke, intracranial aneurysm, carotid artery stenosis, and cerebral hypoperfusion. A narrative literature review was conducted using anatomical, radiological, and clinical studies focusing on the morphology of the Circle of Willis, computed tomography angiography, magnetic resonance angiography, digital subtraction angiography, cerebrovascular disease, and cerebral collateral circulation. The available evidence indicates that complete classical anatomy is present only in a proportion of the population, while hypoplastic or absent communicating arteries are among the most frequent variations.

Keywords: Circle of Willis, cerebral arteries, anatomical variation, cerebrovascular disease, ischemic stroke, intracranial aneurysm, cerebral collateral circulation, angiography.

Introduction. The human brain requires a continuous and adequate blood supply because neuronal tissue is highly sensitive to oxygen and glucose deprivation. Cerebral blood flow is primarily provided by two major arterial systems: the internal carotid arteries, which form the anterior cerebral circulation, and the vertebral arteries, which unite to form the basilar artery and contribute to the posterior cerebral circulation. These systems are interconnected through the Circle of Willis, an arterial network located at the base of the brain. The Circle of Willis is formed by the anterior cerebral arteries, the anterior communicating artery, the terminal portions of the internal carotid arteries, the posterior communicating arteries, and the proximal segments of the posterior cerebral arteries. In the classical anatomical configuration, these vessels form a complete arterial ring that provides potential collateral pathways between the right and left sides of the cerebral circulation and between the anterior and posterior circulations. The main physiological importance of the Circle of Willis lies in its ability to redistribute cerebral blood flow when one of the major feeding arteries becomes



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narrowed or occluded. Under normal conditions, the amount of blood crossing the communicating arteries may be relatively low. However, if a major vessel such as the internal carotid artery becomes stenosed, pressure gradients may develop across the communicating arteries and activate compensatory collateral flow.¹

Despite the classical depiction of a complete and symmetrical Circle of Willis in anatomical textbooks, numerous anatomical and radiological studies have demonstrated considerable variability in this vascular system. A complete circle is not present in all individuals, and variations such as hypoplasia, aplasia, asymmetry, duplication, fenestration, and fetal-type posterior cerebral artery are frequently observed.

These variations have important clinical significance. The effectiveness of collateral circulation depends on the continuity and caliber of the communicating arteries. A hypoplastic or absent vessel may limit compensatory blood flow and increase vulnerability to cerebral ischemia. Conversely, a well-developed collateral network may help preserve cerebral perfusion during arterial obstruction. The Circle of Willis is also clinically relevant in intracranial aneurysm formation. Aneurysms frequently develop at arterial branching points, especially around the anterior communicating artery and posterior communicating artery. Anatomical asymmetry and variation in vessel caliber may alter local hemodynamic forces and contribute to vascular wall stress. The increasing use of computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography has improved the ability to visualize cerebral arterial anatomy in living patients. These imaging techniques are especially important in the evaluation of ischemic stroke, carotid artery disease, intracranial aneurysms, and preoperative neurovascular planning. The aim of the present study was to review the major anatomical variations of the Circle of Willis and evaluate their clinical significance in cerebrovascular disease, particularly ischemic stroke, carotid artery stenosis, intracranial aneurysm, and cerebral hypoperfusion.

MATERIALS AND METHODS

A narrative review of the scientific literature was conducted to evaluate the anatomical characteristics and clinical relevance of variations in the Circle of Willis. Publications concerning normal cerebral arterial anatomy, congenital vascular variations, cerebral collateral circulation, ischemic stroke, carotid artery disease, intracranial aneurysms, computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography were reviewed. The literature included cadaveric anatomical studies as well as radiological and clinical investigations. Particular attention was given to studies assessing the completeness of the Circle of Willis, the prevalence of hypoplastic and aplastic segments, fetal-type posterior cerebral artery, arterial asymmetry, duplication, fenestration, and their relationship with cerebrovascular disease. The reviewed evidence was analyzed according to several principal categories: normal anatomy of the Circle of Willis, variations of the anterior communicating artery, posterior communicating artery abnormalities, fetal-type posterior cerebral artery, incomplete arterial configurations, collateral circulation, and clinical implications in ischemic and hemorrhagic cerebrovascular disorders.

Only previously published data were analyzed. No direct intervention on human participants or collection of identifiable patient data was performed. Therefore, institutional ethical approval was not required for this literature-based study.

RESULTS

The reviewed literature demonstrated that the anatomical configuration of the Circle of Willis varies considerably among individuals. Although the classical complete arterial ring is commonly presented as the standard pattern, many individuals demonstrate one or more deviations from this configuration. One of the most frequent abnormalities involves the posterior communicating arteries.

¹ Krabbe-Hartkamp M.J., van der Grond J., de Leeuw F.E., et al. Circle of Willis: morphologic variation on three-dimensional time-of-flight MR angiograms. *Radiology*. 1998;207(1):103–111.



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These vessels may be small, hypoplastic, or completely absent on one or both sides. Because the posterior communicating arteries connect the internal carotid circulation with the posterior cerebral circulation, their absence may reduce the capacity of the brain to compensate for reduced blood flow in one of these systems. Variations of the anterior communicating artery are also common. This vessel may be hypoplastic, duplicated, fenestrated, or occasionally absent. The anterior communicating artery is especially important because it provides a pathway for blood flow between the right and left anterior cerebral circulations. In cases of severe unilateral carotid stenosis, a well-developed anterior communicating artery may permit compensatory blood flow from the contralateral side. Anatomical asymmetry of the A1 segments of the anterior cerebral arteries is frequently reported. In some individuals, one A1 segment may be significantly smaller than the other. In such cases, both anterior cerebral arteries may receive a dominant blood supply from one internal carotid artery through the anterior communicating artery. This pattern can significantly alter cerebral hemodynamics. Another clinically important variant is the fetal-type posterior cerebral artery. During normal embryological development, the posterior cerebral artery initially receives blood mainly from the internal carotid artery through the posterior communicating artery. As development progresses, the vertebrobasilar system becomes the dominant source of blood supply to the posterior cerebral artery. If this developmental transition remains incomplete, the posterior cerebral artery continues to arise predominantly from the internal carotid artery. This configuration is referred to as fetal-type posterior cerebral artery. In a complete fetal-type posterior cerebral artery, the P1 segment is absent, while in a partial fetal-type configuration the P1 segment is present but smaller than the posterior communicating artery. This variation may result in a situation where the posterior cerebral territory is supplied primarily by the carotid circulation.

The reviewed studies also showed that the completeness of the Circle of Willis may influence the effectiveness of cerebral collateral circulation. Individuals with a complete and well-developed arterial circle generally possess more potential pathways for redistribution of blood during arterial obstruction. In contrast, patients with absent or severely hypoplastic communicating arteries may have limited collateral capacity. In ischemic stroke, the extent of cerebral tissue damage depends not only on the location and duration of arterial occlusion but also on the strength of collateral circulation. Patients with effective collateral networks may maintain perfusion of ischemic brain tissue for a longer period, potentially slowing the progression of irreversible injury. The anatomy of the Circle of Willis is also relevant in carotid artery stenosis. In severe unilateral carotid stenosis, collateral blood flow may pass through the anterior communicating artery from the opposite internal carotid artery or through the posterior communicating artery from the vertebrobasilar system. If these vessels are absent or hypoplastic, compensatory perfusion may be insufficient.

A relationship between variations of the Circle of Willis and intracranial aneurysms has also been reported. Aneurysms frequently occur around the anterior communicating artery, posterior communicating artery, and other arterial bifurcations. Variations in vessel size and symmetry may contribute to altered hemodynamic stress at these sites.

DISCUSSION

The findings of this review confirm that the Circle of Willis demonstrates substantial anatomical diversity. The classical complete arterial configuration should therefore be considered an ideal anatomical model rather than a universal pattern. The principal clinical importance of the Circle of Willis lies in its function as a primary cerebral collateral network. When the blood supply through one major artery is compromised, the communicating vessels can redistribute blood and help maintain perfusion of vulnerable brain tissue. The effectiveness of this mechanism depends strongly on vascular anatomy. If the anterior communicating artery is well developed, blood may cross from the opposite carotid system and maintain anterior cerebral circulation in the presence of unilateral carotid occlusion. If this vessel is absent or severely hypoplastic, the ability to compensate may be significantly reduced. The posterior communicating arteries perform a similar function between the



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anterior and posterior cerebral circulations. Their anatomical development may therefore determine the extent to which vertebrobasilar blood flow can compensate for carotid insufficiency or vice versa. Fetal-type posterior cerebral artery is particularly important in clinical neurology and neuroradiology. In this variant, posterior cerebral territories become more dependent on the internal carotid artery. Consequently, carotid embolism or carotid artery stenosis may produce posterior circulation ischemic lesions. This may complicate interpretation of stroke mechanisms because a posterior cerebral artery infarction may originate from carotid disease rather than from vertebrobasilar pathology. The Circle of Willis also plays a significant role in determining the severity and distribution of ischemic stroke. A patient with robust collateral circulation may preserve adequate blood flow for a longer period after major arterial occlusion. This may influence infarct size, neurological deficit, and potentially the response to reperfusion therapy.

However, the mere anatomical presence of a communicating artery does not necessarily guarantee adequate functional collateral flow. Vessel caliber, pressure gradients, vascular resistance, and distal arterial conditions also influence blood redistribution. Therefore, anatomical imaging should be interpreted together with clinical findings and perfusion studies when necessary.

The relationship between anatomical variations and intracranial aneurysms is also clinically important. The anterior communicating artery is one of the most common sites of intracranial aneurysm formation. Unequal A1 segments may cause asymmetrical blood flow through the anterior communicating artery, potentially increasing local wall stress. Similarly, posterior communicating artery aneurysms arise at a region where hemodynamic forces are complex.² Variant anatomy can modify these forces and may contribute to aneurysm development, although anatomical variation alone is not sufficient to explain aneurysm formation. Detailed knowledge of the Circle of Willis is essential before neurosurgical and endovascular interventions. Procedures such as aneurysm clipping, endovascular coiling, flow diversion, carotid endarterectomy, carotid artery stenting, and mechanical thrombectomy require careful assessment of cerebral arterial anatomy. Computed tomography angiography is particularly useful in emergency settings because it rapidly demonstrates intracranial arterial occlusion, aneurysm morphology, and major vascular variants. Magnetic resonance angiography provides noninvasive evaluation without ionizing radiation and is widely used for cerebral vascular assessment. Digital subtraction angiography remains highly valuable in complex cases because it provides excellent spatial and temporal resolution and allows dynamic evaluation of collateral flow. Modern image processing may further improve visualization of the Circle of Willis. Three-dimensional reconstructions provide detailed information about the spatial relationships of cerebral vessels. Artificial intelligence-based image analysis may also assist in automatic segmentation, detection of vascular anomalies, and assessment of collateral circulation in the future. One limitation of the available literature is the lack of a single standardized definition of arterial hypoplasia. Different studies use different diameter thresholds, which can influence the reported prevalence of incomplete Circle of Willis configurations. Population differences and imaging techniques also contribute to variation in results.

Future research should focus on combining anatomical imaging with cerebral perfusion assessment. Such an approach may help determine not only whether a vascular variant is present but also whether it has meaningful functional consequences for cerebral hemodynamics.

CONCLUSION

The Circle of Willis is an anatomically variable and clinically important arterial network that plays a central role in maintaining cerebral perfusion. A complete and symmetrical configuration is not present in all individuals, and variations such as hypoplasia, aplasia, duplication, fenestration, asymmetry, and fetal-type posterior cerebral artery are frequently encountered. These anatomical

² Hendrikse J., van Raamt A.F., van der Graaf Y., Mali W.P.T.M., van der Grond J. Distribution of cerebral blood flow in the Circle of Willis. *Radiology*. 2005;235(1):184–189.



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variants may influence the effectiveness of cerebral collateral circulation and may modify the clinical consequences of carotid artery stenosis, major arterial occlusion, ischemic stroke, and intracranial aneurysm. A well-developed Circle of Willis can provide important compensatory blood flow during vascular obstruction, whereas incomplete or hypoplastic communicating pathways may increase vulnerability to cerebral hypoperfusion. Fetal-type posterior cerebral artery has particular clinical relevance because it shifts the blood supply of the posterior cerebral territory toward the internal carotid circulation and may alter the mechanism and distribution of ischemic stroke. Detailed understanding of Circle of Willis anatomy is essential for neurologists, neurosurgeons, radiologists, vascular surgeons, and interventional specialists. Computed tomography angiography, magnetic resonance angiography, and digital subtraction angiography are important tools for identifying vascular variants and planning treatment.

Integration of anatomical, hemodynamic, and functional imaging information may provide a more individualized assessment of cerebrovascular risk and improve clinical decision-making in patients with cerebrovascular disease.

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