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Original Research Article

A Retrospective Cadaveric Study of Anatomical Variations of the Circle of Willis

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Abstract:

Background: The Circle of Willis is an important arterial anastomotic network at the base of the brain that provides potential collateral communication between the anterior and posterior cerebral circulations. It demonstrates significant inter-individual anatomical variability with possible repercussions in cerebral haemodynamics, collateral blood flow, neurovascular imaging and surgery.

Objective: The objective of the present study was to evaluate the anatomical variations, completeness, symmetry and morphologic configurations of the Circle of Willis in human cadaveric brain specimens.

Methodology: Descriptive cadaveric study was done in Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar, India for three months. Sixty formalin fixed human cadaveric brain specimens were systematically examined. Arterial elements were evaluated for completeness, symmetry, calibre, hypoplasia, aplasia, duplication, fenestration and other morphological variations. Descriptive statistics were used to record and analyze the data.

Result: 63.3% of specimens had a complete Circle of Willis, and 36.7% had an incomplete Circle. Hypoplasia was most common (33.3%), with next most common being variations in arterial size (26.7%) and asymmetry (20.0%). The most common site involved was the posterior communicating artery (21.7%). 70.0% of specimens were found to have bilateral symmetry.

Conclusion: Results showed that there is significant anatomical variation of the COW with more than a complete and symmetrical circle of Willis. Familiarity with these variations is crucial in anatomical knowledge and for clinical practice in neurosurgery and neuroscience.

Keywords: Circle of Willis; Anatomical Variation; Cadaveric Study; Cerebral Arteries; Hypoplasia; Asymmetry; Posterior Communicating Artery.

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Introduction

The Circle of Willis (CoW) or circulus arteriosus cerebri is a circulatory system of arteries located at the base of the brain. It is important for connecting the anterior and posterior cerebral circulations and is responsible for a major contribution to cerebral blood flow via collateral pathways. Thomas Willis, an English physician, described it in detail in his book, Cerebri Anatomy (1664). However, before his description, there had been observations by anatomists such as Fallopius, Casserius and Vesling, who had increasingly described the course of the arteries at the base of the brain. Willis and his colleagues laid the groundwork for the comprehension of the arterial circle and its role in the cerebral circulation [1,2].

The Circle of Willis is actually made up of vessels from both the internal carotid and vertebrobasilar systems. The internal carotid arteries end as the anterior cerebral artery (ACA) and middle cerebral artery (MCA) and provide origin to the posterior communicating artery (PCoA). The anterior cerebral arteries are joined by the anterior communicating artery (ACoA). The basilar artery is created by the joining of the right and left vertebral arteries and ends by splitting into the right and left posterior cerebral arteries (PCAs). There is a posterior communicating artery which links each PCA to the internal carotid artery. Therefore, the main components of the arterial circle are the ACoA, proximal segments of the ACAs, PCoAs and proximal segments of the PCAs [3,4].

The significance of the Circle of Willis is mostly its ability to provide collateral circulation. The major cerebral arteries are chiefly responsible for blood flow to the brain under normal circumstances. When an arterial segment is narrowed or occluded, the communicating arteries can allow blood to be redistributed between the anterior and posterior circulation. The size, symmetry and continuity of the communicating vessels have a significant effect on the effectiveness of this collateral pathway. Therefore, such anatomical differences which have less potential for collateral flow may have clinical implications in patients with cerebrovascular disease [5].

The Circle of Willis is commonly illustrated as a bilateral and complete polygon of arteries, but the classic Circle of Willis is relatively rare. Many anatomical variations have been described in cadaveric and radiological examinations. Variations include the presence or absence of its component arteries, as well as their size, origin, course or branching pattern. Common vascular anomalies include hypoplasia or aplasia of the anterior or posterior communicating arteries, anterior cerebral artery asymmetry, duplication or fenestration of arteries and posterior cerebral circulation variations [6,7]. A cadaveric study of 75 human brains [8] reported 20 abnormalities and 55 with the conventional pattern, the abnormalities included the anterior communicating artery, posterior communicating artery, anterior cerebral artery and posterior cerebral artery.

Of the posterior communicating artery, one of the most common locations of anatomical variation of the Circle of Willis, it is particularly variable. It was found from a systematic review and meta-analysis by Jones et al. that there is a significant variation in the prevalence of the Circle of Willis configurations, especially the morphology and size of the posterior communicating artery (PcomA) [6]. Likewise, a cadaveric study of Malawian population showed a great variation in the distribution of the Circle of Willis variants and thus the frequency of occurrence of individual anatomical pattern may vary from one population to another [7]. All of these observations suggest that there could be geographical or population related variations that could account for the morphology of the cerebral arterial circle.

Anatomical variations of the Circle of Willis are not just of anatomical interest but can have clinical significance. Changes of vessel diameter, asymmetry and incomplete arterial connections may affect cerebral hemodynamics and change the ability of the arterial circle to compensate for arterial obstruction. Some types have also been linked to the formation and rupture of blood vessels within the brain. In addition, a systematic review and meta-analysis found that an A1 segment that is hypoplastic or aplastic is significantly associated with ACoA aneurysms and that a fetal-type posterior cerebral artery (PComA) configuration is significantly associated with PComA aneurysms [9]. Thus, an understanding of Willis morphology is pertinent to the understanding of cerebrovascular disorders, intracranial aneurysms, ischemic events and neurovascular interventions.

Cadaveric dissection is still a useful tool for the detailed morphology of the cerebral arteries as it allows direct visualization of the vessels and their relationships, branching patterns and subtle variations which are not always appreciated from imaging alone. Anatomical studies have previously shown that direct examination of cadaveric specimens can reveal variations both in the anterior part and the posterior part of the arterial circle [10]. A systematic study of these differences can therefore help to build a database of the anatomy of the population in question and offer valuable information to the clinical, radiological, neurosurgical and anatomical fields.

Given the high degree of variation in the morphology of the Circle of Willis and the clinical relevance of this circulus, it is important to document anatomical variations of the Circle of Willis in different populations. But the population-specific cadaveric data from other geographical regions of India are still useful in determining the incidence and distribution of these variations. Therefore, the present retrospective cadaveric study was carried out in the Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar, India with the aim of studying the anatomical variations in the Circle of Willis in cadaveric specimens. The study is designed to describe the pattern and distribution of the variations within its component arteries and thus add to the knowledge of the normal, anatomical and clinically relevant pattern of the cerebral arterial circulation.

Methodology

Study Design: The present study was designed as a retrospective descriptive cadaveric observational study to assess the anatomical variations of the Circle of Willis in human cadaveric brain specimens. The study focused on identifying and documenting variations in the components of the Circle of Willis, including hypoplasia, aplasia, duplication, fenestration, asymmetry, differences in arterial dimensions, incomplete configuration, and other abnormal arterial architectures. The morphology and completeness of the arterial circle were systematically examined and recorded for each specimen.

Study Area: The study was conducted in the Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar, India. The study involved the examination of human cadaveric brain specimens available in the Department of Anatomy. The observations were carried out by the Senior

Resident, Department of Anatomy, under appropriate departmental supervision.

Study Duration: The study was conducted over a period of 3 months.

Sample Size: A total of 60 formalin-preserved human cadaveric brain specimens (N = 60) were included in the present study. Each specimen was considered as an individual observational unit for assessment of the Circle of Willis and its anatomical variations.

Sample Population: The study population consisted of human cadaveric brain specimens available in the Department of Anatomy during the study period. Formalin-preserved brains suitable for adequate visualization and examination of the cerebral arterial circulation were selected for the study.

Data Collection: Data were collected through the systematic anatomical examination of 60 formalin-preserved human cadaveric brain specimens available in the Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar, India.

Each specimen was assigned a unique identification number before examination. The skull cap was removed by making a circumferential incision approximately 1 cm above the supraorbital margin anteriorly and at the level of the external occipital protuberance posteriorly using a saw. The skull cap was then carefully separated with the help of a hammer.

The dura mater was incised and reflected, and the brain was gently separated from the cranial cavity. The olfactory nerves were first detached by elevating the frontal lobe. This was followed by careful division of the optic nerves, internal carotid arteries, infundibulum, and oculomotor nerves. The attached margins of the tentorium cerebelli and falx cerebelli were subsequently incised, and the remaining cranial nerves were carefully divided. The medulla oblongata was incised at the level of the foramen magnum, following which the brain was gently removed from the cranial cavity.

The specimens were washed with tap water and placed in appropriately labelled containers containing 10% formalin for preservation. Following adequate fixation, the basal surface of each brain was cleaned, and the arachnoid mater surrounding the cerebral arteries was carefully removed to expose the Circle of Willis.

The Circle of Willis was identified and systematically examined for its shape, completeness, symmetry, arterial configuration, and morphological variations. Its individual components, including the anterior cerebral arteries, anterior communicating artery, internal carotid arteries, posterior communicating arteries, and posterior cerebral arteries, were examined for hypoplasia, aplasia, duplication, fenestration, and differences in arterial dimensions between corresponding vessels.

Any abnormal arterial architecture or variation in the configuration of the Circle of Willis was documented. All observations were recorded in a structured data collection sheet. Representative specimens showing significant anatomical variations were photographed and labelled according to their respective identification numbers. The recorded observations were subsequently compiled into a master database for statistical analysis.

Inclusion Criteria

The following specimens were included in the study:

- Human cadaveric brain specimens are available in the Department of Anatomy during the study period.
- Specimens adequately preserved in formalin and suitable for anatomical examination.
- Specimens in which the basal surface of the brain and arterial components of the Circle of Willis could be adequately exposed.
- Specimens in which the major components of the Circle of Willis could be identified sufficiently for morphological assessment.
- Properly labelled specimens with adequate documentation for inclusion in the study.

Exclusion Criteria

The following specimens were excluded from the study:

- Cadaveric brain specimens with severe decomposition or inadequate preservation.
- Specimens with extensive traumatic damage to the basal surface of the brain or cerebral arteries.
- Specimens in which the Circle of Willis could not be adequately exposed or identified.
- Specimens with severe pathological or surgical alterations that prevented reliable assessment of normal arterial anatomy.
- Specimens with incomplete identification or inadequate documentation.

Procedure for Assessment of the Circle of Willis: After adequate fixation and preparation of each specimen, the basal aspect of the brain was positioned appropriately for examination. The arachnoid membrane was carefully removed from the region of the Circle of Willis and its surrounding arteries. The arterial components were cleaned and exposed without disturbing their anatomical relationships.

The Circle of Willis was examined systematically from anterior to posterior and from right to left. The presence, continuity, calibre, symmetry, and configuration of the major arterial components were documented. Each component was assessed for the presence of hypoplasia, aplasia, duplication, fenestration, or other morphological abnormalities.

The completeness of the Circle of Willis was assessed according to the continuity of its arterial components. Specimens were categorized according to the observed morphological configuration. Differences in arterial dimensions between corresponding vessels on the two sides were also documented. Particular attention was given to the anterior communicating artery, posterior communicating arteries, anterior cerebral arteries, internal carotid arteries, and posterior cerebral arteries.

All identified variations were photographed for permanent documentation. The findings from each specimen were entered into a standardized data collection sheet and subsequently compiled into a master database for statistical analysis.

Statistical Analysis: The collected data were entered into Microsoft Excel and subsequently analyzed using SPSS software. Descriptive statistical methods were primarily used because the study was observational and focused on documenting anatomical variations.

Categorical variables such as the presence or absence of a particular variation, hypoplasia, aplasia, duplication, fenestration, completeness, symmetry, and different morphological patterns were expressed as frequencies and percentages. Continuous measurements, wherever obtained, were summarized using mean ± standard deviation (SD) and, where appropriate, minimum and maximum values.

The prevalence of individual anatomical variations was calculated as:

Prevalence (%) = (Number of specimens showing the variation / Total number of specimens examined) × 100

Where comparison between categorical variables was required, the Chi-square test or Fisher's exact test, as appropriate, was used. A p-value < 0.05 was considered statistically significant.

The final results were presented using appropriate tables, figures, and photographic documentation to provide a comprehensive description of the anatomical variations observed in the Circle of Willis".

Result

Table 1 shows the distribution of complete and incomplete configurations of the Circle of Willis among the 60 examined cadaveric brain specimens. A complete Circle of Willis was observed in 38 specimens (63.3%), whereas an incomplete configuration was identified in 22 specimens (36.7%). Thus, the complete configuration was more frequently observed than the incomplete configuration in the present study.

Table 1: Completeness of the Circle of Willis among the examined cadaveric brain specimens

Completeness of Circle of Willis	Number of specimens (n)	Percentage (%)
Complete Circle of Willis	38	63.3
Incomplete Circle of Willis	22	36.7
Total	**60**	**100**

Table 2 presents the distribution of different morphological variations observed in the Circle of Willis. Hypoplasia was the most frequently observed variation, occurring in 20 specimens (33.3%), followed by differences in arterial dimensions in 16 specimens (26.7%) and asymmetry in 12 specimens (20.0%). Aplasia was observed in 8 specimens (13.3%), while duplication and fenestration were found in 4 (6.7%) and 2 (3.3%) specimens, respectively. Since more than one variation could be present in the same specimen, the cumulative percentage exceeded 100%.

Note: Multiple variations could be present in a single specimen; therefore, the total exceeds 60.

The total exceeds 100% because some specimens exhibited more than one anatomical variation.

Table 2: Distribution of morphological variations observed in the Circle of Willis

Morphological variation	Number of specimens (n)	Percentage (%)
Hypoplasia	20	33.3
Asymmetry	12	20
Aplasia	8	13.3
Duplication	4	6.7
Fenestration	2	3.3
Difference in arterial dimensions	16	26.7
Total observations	**62**	**103.3**

Table 3 shows the distribution of anatomical variations according to the individual arterial components of the Circle of Willis. The posterior communicating artery showed the highest frequency of variations, involving 13 specimens (21.7%), followed by the anterior cerebral artery with variations in 10 specimens (16.7%). Variations of the anterior communicating artery were observed in 5 specimens (8.3%), while the posterior cerebral artery and internal carotid artery were affected in 3 (5.0%) and 2 (3.3%) specimens, respectively. Hypoplasia was the most frequently observed type of variation among the arterial components.

Table 3: Distribution of variations according to individual components of the Circle of Willis

Arterial component	Hypoplasia n (%)	Aplasia n (%)	Duplication n (%)	Fenestration n (%)	Total specimens with variation n (%)
Anterior cerebral artery	5 (8.3)	2 (3.3)	2 (3.3)	1 (1.7)	10 (16.7)
Anterior communicating artery	2 (3.3)	1 (1.7)	1 (1.7)	1 (1.7)	5 (8.3)
Internal carotid artery	1 (1.7)	1 (1.7)	0 (0.0)	0 (0.0)	2 (3.3)
Posterior communicating artery	10 (16.7)	3 (5.0)	1 (1.7)	0 (0.0)	13 (21.7)
Posterior cerebral artery	2 (3.3)	1 (1.7)	0 (0.0)	0 (0.0)	3 (5.0)

Table 4 presents the distribution of specimens according to the symmetry of the Circle of Willis. Bilateral symmetry was observed in 42 specimens (70.0%), making it the predominant pattern. Mild asymmetry was identified in 10 specimens (16.7%), whereas marked asymmetry was observed in 8 specimens (13.3%). Therefore, symmetrical arterial configuration was more common than asymmetrical configuration in the examined specimens.

Table 4: Symmetry of the arterial components of the Circle of Willis

Symmetry pattern	Number of specimens (n)	Percentage (%)
Bilaterally symmetrical	42	70
Mild asymmetry	10	16.7
Marked asymmetry	8	13.3
Total	**60**	**100**

Table 5 shows the different morphological configurations of the Circle of Willis observed in the study. A complete and symmetrical configuration was the most common pattern, observed in 28 specimens (46.67%), followed by an incomplete configuration due to hypoplasia in 12 specimens (20.00%). A complete Circle of Willis with minor anatomical variations was observed in 10 specimens (16.67%), while incomplete configurations due to aplasia and other causes were identified in 6 (10.00%) and 4 (6.66%) specimens, respectively.

Table 5: Morphological configuration of the Circle of Willis

Morphological configuration	Number of specimens (n)	Percentage (%)
Complete and symmetrical	28	46.67
Complete with minor anatomical variation	10	16.67
Incomplete due to hypoplasia	12	20
Incomplete due to aplasia	6	10
Other incomplete configurations	4	6.66
Total	**60**	**100**

Table 6 presents the distribution of right-sided, left-sided, and bilateral arterial variations. Hypoplasia was observed in 7 right-sided (11.7%), 6 left-sided (10.0%), and 7 bilateral (11.7%) cases. Aplasia was identified in 3 right-sided (5.0%), 2 left-sided (3.3%), and 3 bilateral (5.0%) cases. Duplication was observed in 2 right-sided (3.3%), 1 left-sided (1.7%), and 1 bilateral (1.7%) case, whereas fenestration was identified in 1 right-sided (1.7%) and 1 left-sided (1.7%) case. Overall, the distribution of arterial variations was relatively comparable between the right and left sides.

Table 6: Distribution of right- and left-sided arterial variations

Arterial variation	Right-sided n (%)	Left-sided n (%)	Bilateral n (%)
Hypoplasia	7 (11.7)	6 (10.0)	7 (11.7)
Aplasia	3 (5.0)	2 (3.3)	3 (5.0)
Asymmetry	6 (10.0)	6 (10.0)	—
Duplication	2 (3.3)	1 (1.7)	1 (1.7)
Fenestration	1 (1.7)	1 (1.7)	0 (0.0)

Discussion

The Circle of Willis (CW) or circulus arteriosus cerebri is an important arterial network at the base of the brain providing potential collateral communication between the anterior and posterior cerebral circulations. The present retrospective cadaveric study revealed that the 60 brain specimens examined showed a significant amount of morphological variation. Complete configuration was seen in 63.3% of the specimens while 36.7% in incomplete configuration. So, the classical complete arterial circle was more common, but a significant number of the circles did not conform to the textbook image. Earlier anatomic studies have also described that a full and symmetrical CW is not present in all cases and variations of the caliber, continuity and arrangement of arteries are also common (*Eftekhar et al., 2006; Kapoor et al., 2008*) [11,12]".

The prevalence of complete configuration in the current study (63.3%) was widespread and similar to anatomical and imaging studies. *De Silva et al* (2009) [13] in Sri Lankan population reported a typical CW in about 52 % which was lower than the present report. A similar variation was also shown by *Kapoor et al.* (2008) where the hypoplastic and absent arterial segments were a major factor for variation. Inter-study variability may be due to population variation, sample size, method of examination and definitions of hypoplasia and incomplete configurations. Hence, the proportion of complete CW in the present series may be due to methodological and classification differences and not necessarily with previous findings.

The most common morphological variation found was hypoplasia (33.3%), followed by differences in artery size (26.7%) and asymmetry (20.0%). Aplasia was detected in 13.3% while duplication and fenestration were relatively rare. The high prevalence of hypoplasia is consistent with earlier findings, that caliber changes of vessels are among the most common abnormalities of CW. Hypoplastic arterial segments as important contributors to CW variation were reported by *Kapoor et al.* (2008) and *Nordon and Rodrigues Junior* (2012) [14] reported that hypoplasia, aplasia, duplication, fusion and plexiform pattern are important morphological variations. These results indicate that the calibre of the arteries is a significant factor that determines the functional strength of the arterial circle.

The most common artery was the posterior communicating artery (PCoA) which was found to be variant in 21.7% of the specimens, especially hypoplasia. This is in line with earlier research which has shown that the PCoA is one of the most variable parts of the posterior CW. *Voljevica et al., (2005)* found that variation of the PCoA and posterior cerebral artery was often observed [15] and *Kapoor et al., (2008)* found that hypoplasia and absence of arteries were the chief factors contributing towards the variation of CW. The second most commonly altered component was the anterior cerebral artery (ACA), varying in 16.7% of the specimens. These differences in the caliber, asymmetry, duplication, and fusion can be seen with ACA variations. Several ACA configurations have been described by Nordon and Rodrigues Junior (2012) and the anatomical and surgical importance of the ACA and anterior communicating artery complex (ACAC) has been stressed by *Rhoton (2002)* [16].

Other variations such as those of the anterior communicating artery (ACoA), posterior cerebral artery (PCA), and internal carotid artery (ICA) were less common. However, these differences are significant as communicating arteries have the potential for collateral circulation. Several ACoA configurations including duplication and absence have been reported by *De Silva et al., 2009* and *Kapoor et al., 2008*. These results indicate that even apparently complete circles can have small structural defects.

Bilateral symmetry was retained in 70.0% of specimens, mild asymmetry in 16.7% and marked asymmetry in 13.3% so that about 30% had some degree of asymmetry. Symmetry was most common, but the percentage of asymmetric configurations reflects individual variations in the size of the cerebral arteries. *Eftekhar et al., (2006)* have also shown significant morphological differences between individuals and different populations that could be due to variations in the process of development and remodeling of cerebral arteries during the prenatal period.

If overall morphological patterns were taken into account incomplete configuration due to hypoplasia was the next most frequent (20.0%) followed by complete configuration with minor anatomical variations (16.67%), incomplete configuration due to aplasia (10.0%) and other incomplete configurations (6.66%). The results suggest that CW should not merely be categorized as complete or incomplete, because it might be only partially correct. A circle can be anatomically complete yet there may be differences in the diameter of the arteries, asymmetry, duplication or other abnormalities, as also pointed out by *Kapoor et al. (2008).*

These differences are clinically relevant and have been investigated in terms of cerebral blood flow. In 125 healthy volunteers, *Tanaka et al. (2006)* [17] made use of magnetic resonance imaging (MRI) to show that the relative contributions of the blood flow from the bilateral internal carotid and basilar arteries were significantly different for CW configuration. The relatively high hypoplasia and asymmetry rates in the present study, therefore, may be of some functional importance, especially when collateral circulation plays a role.

The CW morphology has also got relevance in surgical and interventional procedures. Kim et al. 2002 [18] reported that CW configuration could predict intraoperative cerebral ischemia and need for shunting during carotid endarterectomy, and *Papantchev et al. 2007* [19] emphasized importance of CW configuration for cerebral protection during aortic surgery. In addition, imaging studies have shown CW variations can be detected in living people, early in life (*Malamateniou et al., 2009*) [20], thus supporting their developmental basis. *Eftekhar et al.* 2006 also emphasized the CW morphology differences among the population.

Cumulative frequencies greater than 100% were possible as there were several different variations within the one specimen. This is not a contradiction, but rather the occurrence of more than one abnormality in the individual. The combinations can affect CW completeness and collateral capacity especially if there are hypoplastic or aplastic communicating arteries.

In general, the present cadaveric retrospective study shows that the Circle of Willis is very variable. While complete configuration (63.3%) and bilateral symmetry (70.0%) were most common, there were also significant percentages of hypoplasia, dimensional differences, asymmetry, aplasia, duplication and fenestration. The majority of hypoplasia (33.3%) and involvement of PCoA (21.7%) was similar to previous studies.

These results suggest that the classical complete and symmetrical CW is not the universal pattern. The knowledge of these variations is important for anatomical teaching, for the interpretation of the angiographic and magnetic resonance imaging findings, for neurosurgical planning and for vascular procedures, and in order to understand individual variations in the potential collateral circulation of the brain.

Conclusion

This retrospective cadaveric study shows huge anatomical variations in the Circle of Willis, both in terms of completeness and symmetry of the circle, calibre of the arteries and morphological configuration. The complete and symmetrical pattern was the most common pattern, but the hypoplasia, aplasia, asymmetry, duplication, fenestration, and other variations of the arteries show that the textbook pattern is not universal. Posterior communicating artery was especially subject to variation which stressed the importance of this artery in the overall morphology and possible collateral circulation of the cerebral arterial system. The clinical significance of these variations is that they can affect the cerebral haemodynamics, collaterals, interpretation of neurovascular imaging and neurosurgical and vascular planning. The results emphasize the need to have a detailed knowledge of the Circle of Willis variants for anatomists, radiologists, neurosurgeons, and other clinicians with interests in the evaluation and treatment of cerebrovascular disease.

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