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Original Research Paper

Anatomy

PROSPECTIVE EVALUATION OF CIRCLE OF WILLIS VARIANTS: ASSOCIATION WITH DEMOGRAPHIC PROFILE AND COMPARATIVE ANALYSIS OF ANTERIOR AND POSTERIOR CIRCULATION

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ABSTRACT

Background: The Circle of Willis (CoW) is a critical arterial network at the base of the brain that safeguards cerebral perfusion through collateral circulation. Variations in its completeness may predispose individuals to ischemic events and influence cerebrovascular outcomes. **Aim:** To evaluate the prevalence of complete and incomplete Circle of Willis and to study its association with age, sex, anterior circulation types, and posterior circulation types. **Materials and Methods:** This cross-sectional study included 550 individuals who underwent angiographic assessment (CT/MR angiography—specify modality). The CoW was classified as complete or incomplete, and anterior and posterior circulation patterns were categorized according to standard criteria. Associations between CoW completeness and demographic as well as vascular parameters were analysed using the Pearson chi-square test. **Results:** A complete Circle of Willis was found in 12.91% of participants, while 87.09% showed an incomplete configuration. No significant association was observed with sex ($p = 0.621$); however, age showed a trend toward decreasing completeness in older groups (provide exact p-value or age range if available). Significant associations were found with both anterior circulation ($\chi^2 = 84.857$, $p < 0.001$) and posterior circulation types ($\chi^2 = 347.713$, $p < 0.001$). Specific variations in the posterior circulation were strongly linked to CoW incompleteness, highlighting their role in determining overall vascular integrity. **Conclusion:** The Circle of Willis is incomplete in the majority of individuals, with completeness declining with advancing age and strongly influenced by anterior and posterior circulation variants rather than sex. Understanding these anatomical patterns is essential for assessing cerebrovascular risk and guiding clinical decision-making.

KEYWORDS : Circle of Willis, age-related variation, completeness, anatomical variation, anterior circulation, posterior circulation, cerebrovascular risk, demographic Profile

INTRODUCTION

The Circle of Willis (CoW) is the fundamental arterial collateral structure of the brain, maintaining cerebral blood flow even when primary vessels are compromised. Its anatomical integrity—or lack thereof—can significantly influence an individual's risk for cerebrovascular events such as ischemic stroke and transient ischemic attacks. Anatomical variants, including vessel hypoplasia and absence, are commonly seen and hold clinical significance, especially before surgical or endovascular procedures.[1]

Three-dimensional time-of-flight (3D-TOF) magnetic resonance angiography (MRA) has emerged as a powerful, non-invasive imaging modality to visualize CoW anatomy. It offers high-resolution depiction of arterial structures without the need for contrast agents or exposure to ionizing radiation.

While numerous studies have documented the prevalence of CoW variants, there remains a notable gap in the literature concerning the relationship between these anatomical patterns and demographic factors such as age and sex, particularly with direct comparisons between anterior and posterior circulation variants. For instance, in a 3D-TOF MRA study of 250 patients, Maaly and Ismail found that the anterior circulation was complete in 68.3% of cases, while the posterior circulation was complete in only 38.3%, with a higher frequency of completeness in younger and female subjects.[2]

Additionally, the Tromsø Study using 3D-TOF angiography in a large population found that complete CoW configuration was relatively rare and that classification schemes allowed systematic categorization of variants.[3] Furthermore, a multi-population study showed that a fully formed CoW was present in just 9.9% of participants, with incomplete configurations becoming more prevalent with advancing age. These findings collectively emphasize the necessity for prospective studies investigating demographic correlates and comparing anterior vs. posterior CoW variants.[4]

This prospective study was undertaken to evaluate the morphological variants of the Circle of Willis using non-contrast 3D-TOF MRA, to determine their association with demographic factors, and to compare the pattern of variations between anterior and posterior circulations. The findings may enhance our understanding of cerebrovascular risk stratification and provide a baseline reference for neurosurgical and interventional procedures.

MATERIAL AND METHODS

This study was a prospective observational study conducted in the Department of Anatomy in collaboration with Department of Radiodiagnosis at R.N.T. Medical College, Udaipur, and Department of Radiodiagnosis at Dr. S.N. Medical College, Jodhpur, Rajasthan, India. Both are tertiary care teaching hospitals that cater to a wide catchment area representing the diverse populations of the Mewar and Marwar regions. Participants meeting the inclusion criteria were consecutively enrolled during the study period to minimize selection bias.

The study protocol was reviewed and approved by the Ethical Committee of the research Institute. Written informed consent was obtained from all participants prior to enrolment. Imaging procedures were non-invasive, carried minimal risk, and were performed in compliance with the Declaration of Helsinki and applicable local regulations. Participant confidentiality was safeguarded by anonymizing all imaging and clinical data and storing it on password-protected systems with access restricted to study investigators.

Participants in this prospective observational study included adults aged 18 to 89 years who underwent MRI examinations for non-vascular indications such as headache, vertigo, or general screening, as well as for non-brain-related clinical evaluations including musculoskeletal, abdominal, or spinal imaging. To ensure adequate statistical power and broad age representation, the study targeted a minimum sample size of

550 individuals. Patients with any history, symptoms, or imaging evidence of cerebrovascular disease were excluded to maintain the accuracy of anatomical evaluation of the Circle of Willis. All eligible individuals provided written informed consent to undergo additional three-dimensional time-of-flight (3D-TOF) magnetic resonance angiography of the Circle of Willis. Patients with a history of stroke, transient ischemic attack, or intracranial arterial stenosis, previous neurosurgical or brain interventions, or the presence of MRI-incompatible implants or metallic foreign bodies were excluded. Individuals unable to tolerate MRI due to severe anxiety or claustrophobia, or those who refused to consent or cooperate during imaging, were also not included in the study.

Magnetic resonance imaging was performed on a Philips 1.5 Tesla Achieva scanner using a dedicated head coil. Non-contrast three-dimensional time-of-flight magnetic resonance angiography (3D-TOF MRA) sequences were acquired to evaluate the Circle of Willis with high spatial resolution. Imaging parameters were optimized to maximize signal-to-noise ratio and ensure accurate visualization of small arterial segments, allowing reliable assessment of arterial anatomy and variations. Imaging was performed on a Siemens MAGNETOM Vida 3-Tesla MRI system equipped with a wide-bore gantry, detachable patient table, and 64-channel head/neck coil. The unit integrates advanced gradient hardware, quiet technology, and ambient lighting to enhance patient comfort while delivering high-resolution 3D time-of-flight angiographic sequences for Circle-of-Willis's evaluation, consistent protocols.

The neuroradiologists reviewed the images blinded to the demographics of the participants. The presence of elements of Circle of Willis, anterior cerebral arteries (ACA) and their continuity, anterior communicating artery (ACoA) and their continuity, internal carotid arteries (ICA) and their continuity, posterior communicating arteries (PCoA) and their continuity, posterior cerebral arteries (PCA) and its continuity, diameter of arteries were only measured. Instruments [greater than] or [greater than or equal to] 0.8 mm were found to be present and < 0.8 mm were considered to be hypoplastic. Anatomical differences given were hypoplasia, aplasia, duplication and fenestration, which were noted and classified.

The scanning sequences applied on MRI were DWI, and GR/T2*WI. MRA was adopted using the 3D-TOF MRA in axial plane with the following parameters: TR 25ms, TE 6.9ms, Relative SNR 1.00, NSA 1, FOV 20 cm × 20 cm × 12.6 cm, matrix 495 × 284 × 180 and slice thickness 0 mm. 180 images were obtained. Images were reported using source images as well as 2D & 3D maximum intensity projections (MIP) and volume rendering (VR) on the Philips Intelli space portal workstation.

Statistical Analysis

Data were analysed using Microsoft Excel (Microsoft Office 2021) and SPSS version 20.0. Descriptive statistics (mean, standard deviation, frequency, percentage) summarized demographic and anatomical findings. Comparisons between anterior and posterior circulation variants were performed using Chi-square analysis. SPSS version 20 was used to conduct the chi square test, two sample Z test and unpaired t test and statistical significance was considered using the alpha level of 0.05.

RESULTS

All 550 participants successfully underwent three-dimensional time-of-flight (3D-TOF) MR angiography of the Circle of Willis (CoW) at our institution using a Philips Achieva 1.5-Tesla scanner. The acquired images were of diagnostic quality in all cases, allowing complete evaluation of circle of willis variants association with demographic profile and comparative analysis of anterior and posterior circulation.

The distribution of Circle of Willis configurations across age groups reveals that incomplete formations are predominant in all categories. Notably, individuals aged 41–60 and 61–80 show the highest frequency of incomplete configurations. The Pearson chi-square test indicates a statistically significant association between age and Circle of Willis completeness (^{2} = 14.400, p = 0.006), suggesting age may influence vascular anatomy. (Table 1) In the examined cohort, completeness of the Circle of Willis did not significantly differ by sex (^{2} = 0.952; p = 0.621). Among females (n=198), 14.65% exhibited a complete circle, whereas 87.09% were incomplete. Males (n=352) showed a similar distribution with 11.93% complete and 88.07% incomplete. These findings suggest that anatomical variations in the Circle of Willis are not markedly influenced by sex, underscoring the general homogeneity of this vascular architecture across genders. (Table 2) In present study, strong relationship between anterior circulation configuration and completeness of the Circle of Willis. All individuals with a complete Circle of Willis also had a complete anterior circulation, whereas none with incomplete anterior circulation had a complete Circle of Willis. The highly significant Pearson chi-square value (^{2} = 92.944, p < 0.001) confirms this association. (Table 3) In relation to posterior circulation and circle of willis, the data clearly demonstrates that all individuals with a complete Circle of Willis also had a complete posterior circulation, while none of those with incomplete posterior circulation had a complete Circle of Willis. This strong association is supported by a highly significant chi-square value (^{2} = 362.419, p < 0.001), indicating a definitive link between posterior circulation status and overall Circle of Willis completeness. (Table 4) In present study, the vast majority of individuals with a complete Circle of Willis fall under Anterior Circulation Type 1. Other types (2 to 6) are almost exclusively associated with incomplete configurations. The Pearson chi-square value (^{2} = 84.857, p < 0.001) confirms a statistically significant association between anterior circulation type and Circle of Willis completeness. (Table 5) In our study, a strong link between posterior circulation types and Circle of Willis configuration. Type A is the only type significantly associated with completeness (69 out of 71 complete cases), while all other types are entirely or almost entirely linked with incomplete configurations. The chi-square value (^{2} = 347.713, p < 0.001) underscores a significant association. (Table 6) The frequency of CoW variants was analysed overall, and their association with demographic factors (age, sex) was evaluated. Additionally, a comparative assessment between anterior and posterior circulation variants was performed to identify which segments showed higher prevalence of hypoplasia or absence.

Table 1: Association Between Age Groups and Circle of Willis Completeness

	Circle of Willis				Total	
Age	Complete		Incomplete			
	No.	%	No.	%	No.	%
≤ 20	8	11.27%	19	3.97%	27	4.91%
21 to 40	19	26.76%	74	15.45%	93	16.91%
41 to 60	21	29.58%	169	35.28%	190	34.55%
61 to 80	20	28.17%	193	40.29%	213	38.73%
> 80	3	4.23%	24	5.01%	27	4.91%
Total	71	12.91%	479	87.09%	550	100%
	Pearson chi-square = 14.400, p-value = 0.006					

Table 2: Association Between Sex and Circle of Willis Completeness

	Circle of Willis				Total	
SEX	Complete		Incomplete			
	No.	%	No.	%	No.	%
Female	29	14.65%	169	85.35%	198	36.00%
Male	42	11.93%	310	88.07%	352	64.00%

Total	71	12.91%	479	87.09%	550	100.00%
Pearson chi-square = 0.952, p-value = 0.621						

Table 3: Association Between Anterior Circulation and Circle of Willis Completeness

	Circle of Willis				Total	
Anterior Circulation	Complete		Incomplete			
	No.	%	No.	%	No.	%
Complete	71	100.00%	186	38.83%	257	46.73%
Incomplete	0	0.00%	293	61.17%	293	53.27%
Total	71	12.91%	479	87.09%	550	100.0%
Pearson chi-square = 92.944, p-value = 0.000						

Table 4: Association Between Posterior Circulation and Circle of Willis Completeness

	Circle of Willis				Total	
Posterior Circulation	Complete		Incomplete			
	No.	%	No.	%	No.	%
Complete	71	70.30%	30	29.70%	101	100.00%
Incomplete	0	0.00%	449	100.00%	449	100.00%
Total	71	12.91%	479	87.09%	550	100.00%
Pearson chi-square = 362.419, p-value = 0.000						

Table 5: Association Between Anterior Circulation Types and Circle of Willis Completeness

	Circle of Willis				Total	
Anterior Circulation	Complete		Incomplete			
	No.	%	No.	%	No.	%
1	69	97.18%	186	38.83%	255	46.36%
2	2	2.82%	112	23.38%	114	20.73%
3	0	0.00%	11	2.30%	11	2.00%
4	0	0.00%	58	12.11%	58	10.55%
5	0	0.00%	60	12.53%	60	10.91%
6	0	0.00%	52	10.86%	52	9.45%
Total	71	12.91%	479	87.09%	550	100.00%
Pearson chi-square = 84.857, p-value = 0.000						

Table 6: Association Between Posterior Circulation Types and Circle of Willis Completeness

	Circle of willis				Total	
Posterior Circulation	Complete		Incomplete			
	No.	%	No.	%	No.	%
A	69	97.18%	30	6.26%	99	18.00%
B	0	0.00%	21	4.38%	21	3.82%
C	0	0.00%	23	4.80%	23	4.18%
D	0	0.00%	218	45.51%	218	39.64%
E	0	0.00%	84	17.54%	84	15.27%
F	0	0.00%	19	3.97%	19	3.45%
G	0	0.00%	18	3.76%	18	3.27%
H	2	0.00%	1	0.21%	1	0.18%
I	0	2.82%	22	4.59%	24	4.36%
J	0	0.00%	8	1.67%	8	1.45%
K	0	0.00%	17	3.55%	17	3.09%
L	0	0.00%	3	0.63%	3	0.55%
M	0	0.00%	2	0.42%	2	0.36%
N	0	0.00%	7	1.46%	7	1.27%
Total	71	14.26%	427	85.74%	550	100.00%
Pearson chi-square = 347.713, p-value = 0.000						

DISCUSSION

In the present study, we evaluated the pattern of CoW variants using 3D-TOF MR angiography, assessed their association with demographic factors such as age and sex, and compared the prevalence of variants in anterior and posterior circulations.

Regarding demographic association, age-related changes were evident. Elderly patients more commonly showed incomplete CoW configurations, possibly due to vessel calibre reduction or atherosclerotic changes. Several previous studies have demonstrated a decline in the prevalence of complete CoW morphology with advancing age, supporting our results. The association with sex was less consistent; while some studies report no significant difference between males and females, others have suggested that incomplete CoW configurations may be slightly more common in males, possibly due to a higher burden of vascular risk factors.

This study examined the integrity of the Circle of Willis (CoW) across different age groups in 550 individuals, revealing a significant decline in CoW completeness with advancing age. Overall, 12.91% demonstrated a complete CoW, while 87.09% had incomplete configurations. Notably, CoW completeness was highest in younger participants (< 20 years: 11.27%; 21–40 years: 26.76%), decreasing progressively in the older age categories (41–60 years: 29.58%; 61–80 years: 28.17%; > 80 years: 4.23%). The association between age and CoW completeness was statistically significant ($\chi^2 = 14.400$, $p = 0.006$). Our findings align well with prior studies demonstrating that CoW completeness inversely correlates with age. In a digital subtraction angiography (DSA)–based study, individuals under 40 were nearly five times more likely to exhibit a complete CoW than older patients, and age remained an independent predictor even after adjusting for hypertension and diabetes (OR: 0.955 per year increase; $p < 0.001$).[5]

Similarly, a large MRI-based investigation reported significantly higher rates of complete CoW configurations in participants younger than 50 years.[2] A broader population study found that only around 11.9% of adults had a complete CoW, with missing posterior communicating arteries being the most common variant—suggesting that incomplete CoW is the prevailing morphology in older adults.[3]

In this study of 550 individuals, we found no significant association between sex and the completeness of the Circle of Willis. Specifically, 14.65% of females had a complete CoW compared to 11.93% of males ($\chi^2 = 0.952$, $p = 0.621$), indicating a comparable distribution of anatomical completeness across sexes. Our findings align with several studies that reported no significant sex-based differences in CoW completeness. For instance, Eftekhar et al.[6] conducted anatomical studies using cadavers and found no meaningful differences between males and females regarding shape, symmetry, or completeness of the CoW. Similarly, Tromsø Study, which used 3D-TOF MRA, also reported that sex did not significantly influence the presence of a complete circle of willies.[3]

Another imaging study reported both age- and sex-related differences in the distribution of complete versus incomplete CoW configurations, with females and younger subjects slightly more likely to have a complete circle.[7] These conflicting findings may be due to different imaging methods, population demographics, or more precise measurement techniques used in recent studies.

In this study, all individuals with a complete Circle of Willis also had a complete anterior circulation, whereas none of the complete CoW cases had anterior circulation defects. Conversely, 61.17% of individuals with an incomplete CoW also showed incomplete anterior circulation. This strong association was statistically significant ($\chi^2 = 92.944$, $p < 0.001$), suggesting that anterior circulation integrity is a major determinant of overall CoW completeness. Our findings are consistent with prior anatomical and angiographic studies that demonstrate the anterior half of the CoW is more frequently complete than the posterior half, and that anomalies in the anterior circulation often define overall CoW incompleteness.[1,3]

Our analysis reveals a striking and highly significant association between posterior circulation completeness and overall CoW completeness ($\chi^2 = 362.419$, $p < 0.001$). In all 71 individuals noted to have a fully complete CoW, the posterior circulation was also intact. Conversely, no individuals with

incomplete CoW had a complete posterior circulation. This suggests that posterior circulation integrity is essential—and perhaps indispensable—for a complete arterial ring at the base of the brain. This observation aligns with recent imaging studies demonstrating that posterior circulation variants are a prime contributor to CoW incompleteness. One such study reported that completeness rates were 60.4% for anterior circulation but just 17.8% for posterior circulation, indicating greater anatomical instability in posterior pathways.[4] Additionally, work exploring demographic anatomical differences confirms that posterior completeness varies more with age and possibly other factors, underscoring its role in collateral stability and vulnerability.[8]

This study demonstrates a strong and statistically significant association between anterior circulation configuration and overall completeness of the Circle of Willis ($\chi^2 = 84.857$, $p < 0.001$). Among individuals with a complete CoW (n = 71), 97.18% had anterior type 1 anatomy, while incomplete CoW was distributed across all other anterior types (2–6). These findings highlight that Type 1 anterior configuration (bilateral normal A1 segments and a patent anterior communicating artery) is the key determinant for maintaining a structurally intact CoW.

Recent imaging studies corroborate our findings, showing that anterior circulation tends to be more stable than posterior circulation, and CoW completeness is largely driven by anterior segment integrity. A high prevalence of anterior type 1 configurations in complete CoW variants has been reported in multiple studies using 3D-TOF MRA and CTA.[8,9]

The present study revealed a highly significant association between the posterior circulation Types configuration and Circle of Willis (CoW) completeness ($\chi^2 = 347.713$, $p = 0.000$). Among individuals with a complete CoW, type A configuration was predominant (97.18%), whereas incomplete CoW cases showed wide variability, most frequently type D (45.51%), followed by types E (17.54%) and C (4.80%). Other posterior circulation variants (B, F–N) were relatively rare and exclusively associated with incomplete CoW morphology, except for type H, where two cases (2.82%) were complete and one case was incomplete. These findings highlight that a complete posterior circulation (type A) strongly correlates with overall CoW completeness, while hypoplastic or aplastic posterior cerebral artery (PCA) segments—as seen in types D, E, and other variants—are strongly associated with an incomplete CoW. This is consistent with prior studies using magnetic resonance angiography (MRA) and computed tomography angiography (CTA), which report that posterior circulation variants are more frequent than anterior circulation anomalies and are major contributors to incomplete CoW morphology (Papantchev et al., 2023; Wright et al., 2024). [10,11]

Other study conducted by Qiu et al., 2024;[12] Li et al., 2024[13] embryologically, this can be explained by the delayed maturation of the posterior circulation compared to the anterior circulation. Persistence of fetal-type PCA, hypoplasia of P1 segments, or absence of the posterior communicating arteries (PCoAs) leads to reduced collateral capacity and incomplete configuration (Vrselja et al., 2023).[14] Clinically, individuals with these variants have been shown to have higher susceptibility to posterior circulation ischemic events, particularly when combined with vertebrobasilar hypoplasia or atherosclerotic disease.

In summary, posterior circulation morphology is a critical determinant of CoW completeness, with type A configuration almost invariably indicating a complete CoW, while other types—especially type D and E—mark significant deviations and reduced collateral potential. These findings underscore the importance of detailed vascular imaging when assessing stroke risk and planning interventions involving the posterior circulation.

CONCLUSION

This study shows that the Circle of Willis (CoW) is complete in only a small proportion of individuals, while most have some form of incomplete configuration. Completeness of the CoW is strongly associated with both anterior and posterior circulation patterns, indicating that variations in these circulations play an important role in the overall integrity of the circle. No significant difference was observed between males and females, but age showed a significant relationship with CoW completeness.

These findings highlight the importance of understanding anatomical variations of the CoW, as they may influence collateral circulation in conditions such as stroke or aneurysm. Knowledge of these patterns can help clinicians and radiologists anticipate cerebrovascular risks and plan appropriate interventions.

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