

Original Research Article

OBSERVATIONAL STUDY OF ANATOMICAL VARIATIONS IN THE CIRCLE OF WILLIS USING CT ANGIOGRAPHY AND THEIR CLINICAL AND NEUROSURGICAL SIGNIFICANCE

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ABSTRACT

Background: The Circle of Willis is an important arterial anastomotic network that maintains collateral cerebral circulation. Considerable anatomical variation may occur in its anterior and posterior components, and these variations can influence cerebral perfusion, interpretation of vascular imaging, and planning of neurosurgical and endovascular procedures. The aim was to evaluate anatomical variations in the Circle of Willis using CT angiography and assess their clinical and neurosurgical significance.

Materials and Methods: This hospital-based observational study included 60 participants of Gujarat region who underwent cerebral CT angiography at a tertiary care hospital. The Circle of Willis was assessed for completeness, hypoplasia, aplasia, duplication, fenestration, fetal-origin posterior cerebral artery, laterality, and involvement of anterior and posterior circulations. Associated findings such as aneurysm, arterial stenosis or occlusion, cerebral infarction, and vascular malformation were also recorded.

Results: Anatomical variations were identified in 42 (70.00%) participants, while 18 (30.00%) had no identifiable variation. A complete Circle of Willis was present in 22 (36.67%), whereas 38 (63.33%) had an incomplete configuration. Posterior communicating artery hypoplasia was the most frequent variation, observed in 17 (28.33%), followed by posterior communicating artery aplasia in 9 (15.00%) and fetal-origin posterior cerebral artery in 8 (13.33%). Posterior circulation-only variations were present in 24 (57.14%) of participants with variants. At least one clinically relevant CTA abnormality was significantly more frequent among participants with anatomical variations than in those without variations (71.43% vs 38.89%; $p=0.023$). Similarly, clinically relevant abnormalities were more frequent in participants with an incomplete Circle of Willis than in those with a complete configuration (73.68% vs 40.91%; $p=0.012$).

Conclusion: Anatomical variations of the Circle of Willis were common on CT angiography, particularly in the posterior circulation. Recognition of these variants is important for cerebrovascular assessment, evaluation of collateral pathways, and planning of neurosurgical and endovascular procedures.

Keywords: Circle of Willis; CT angiography; Anatomical variations; Cerebral circulation; Neurosurgery.

INTRODUCTION

The Circle of Willis is an arterial anastomotic network situated at the base of the brain and constitutes an important connection between the

anterior and posterior cerebral circulations. It is formed by the terminal portions of the internal carotid arteries, proximal segments of the anterior cerebral arteries, anterior communicating artery, posterior communicating arteries, and proximal segments of

the posterior cerebral arteries. Through these communicating channels, the circle provides an alternative pathway for redistribution of cerebral blood flow when the normal supply through one of the major feeding arteries is reduced or interrupted. The anatomical integrity and calibre of its constituent arteries therefore play an important role in maintaining adequate cerebral perfusion and protecting vulnerable brain tissue from ischemia.^[1] Although traditionally illustrated as a symmetrical and complete arterial polygon, considerable anatomical variability occurs within the Circle of Willis. Variations may affect either the anterior or posterior components and may include hypoplasia, aplasia, duplication, fenestration, asymmetry, persistence of embryonic arterial patterns, and altered origins of individual vessels. The posterior communicating arteries, anterior communicating artery, A1 segments of the anterior cerebral arteries, and P1 segments of the posterior cerebral arteries are particularly prone to morphological variability. Vessel calibre and configuration may also differ according to demographic and anatomical factors. Recognition of this variation is important because an apparently minor difference in arterial anatomy may substantially modify cerebral blood-flow distribution and the availability of collateral pathways during vascular compromise.^[2] The functional significance of the Circle of Willis becomes particularly evident in cerebrovascular disease. In the presence of stenosis, occlusion, embolism, or other interruption of a major cerebral artery, an adequately developed communicating pathway may facilitate compensatory blood flow to the affected vascular territory. Conversely, hypoplastic or absent segments may restrict collateral recruitment and alter the expected distribution of ischemic injury. Anatomical variants can also modify the vascular territories supplied by individual arteries. For example, persistence of fetal-type posterior cerebral circulation may result in a portion of the posterior cerebral territory receiving its principal supply from the internal carotid system. Awareness of such configurations is important for accurate localization of ischemic lesions and interpretation of stroke mechanisms.^[3] Anatomical variations of the Circle of Willis are also relevant to the development, location, evaluation, and treatment of intracranial aneurysms. Variations that produce asymmetrical arterial flow or modify vascular resistance may alter local hemodynamic forces at arterial bifurcations and communicating vessels. The anterior communicating and posterior communicating arterial regions are particularly important because they represent common sites requiring detailed vascular assessment before surgical or endovascular intervention. Precise recognition of hypoplastic, absent, duplicated, or unusually configured arteries can influence interpretation of aneurysm morphology and selection of an operative corridor. It can also help prevent inadvertent compromise of an artery that may represent an essential collateral pathway to a cerebral

territory.^[4] Age-related vascular alterations further increase the importance of understanding Circle of Willis morphology. Structural characteristics of cerebral arteries coexist with acquired changes such as atherosclerosis, stenosis, vessel wall degeneration, and reduction in arterial compliance. In individuals with reduced inflow through the carotid or vertebrobasilar systems, the effectiveness of the Circle of Willis as a collateral network depends not only on the presence of communicating vessels but also on their calibre and functional capacity. Hypoplastic components may be insufficient to accommodate increased compensatory flow when demand suddenly rises. Detailed anatomical evaluation is therefore relevant in older patients and in individuals with cerebrovascular risk factors, particularly when cerebral perfusion may depend substantially on collateral redistribution.^[5] The configuration of the Circle of Willis also has considerable importance in neurosurgical and vascular procedures. Surgical clipping of intracranial aneurysms, carotid endarterectomy, temporary arterial occlusion, skull-base surgery, cerebral revascularization, and endovascular interventions may alter blood flow through one or more major arteries. In these situations, knowledge of the available collateral channels can assist in estimating how interruption of a vessel may affect downstream cerebral perfusion. Preoperative demonstration of absent or hypoplastic communicating arteries is particularly relevant when temporary or permanent vessel occlusion is anticipated. Assessment of Circle of Willis anatomy can therefore contribute to operative planning, selection of protective measures, and interpretation of perioperative neurological changes.^[6]

MATERIALS AND METHODS

The present study was conducted as a hospital-based observational study at a tertiary care hospital in Gujarat region. A total of 60 participants who underwent computed tomography angiography (CTA) of the cerebral circulation for clinically indicated neurological or neurosurgical evaluation were included. The study was designed to assess the anatomical configuration of the Circle of Willis, determine the frequency and pattern of its anatomical variations, and evaluate their possible clinical and neurosurgical significance. Participants fulfilling the predefined eligibility criteria were enrolled consecutively. No alteration in routine clinical management was made for the purpose of the study. The study included 60 participants of either sex who underwent cerebral CT angiography and had images of adequate diagnostic quality for evaluation of the Circle of Willis and its major arterial components. Demographic and relevant clinical information, including age, sex, presenting symptoms, indication for CT angiography, and associated neurological or cerebrovascular findings, was recorded in a

structured data collection form. Participants were categorized according to age groups and sex to assess the possible relationship between demographic characteristics and anatomical variations.

Inclusion Criteria

Participants aged 18 years or above who underwent cerebral CT angiography for evaluation of suspected or established cerebrovascular, neurological, or neurosurgical conditions were included. Only examinations in which the intracranial arterial circulation, including the complete Circle of Willis, was adequately visualized and technically suitable for interpretation were considered eligible. Both symptomatic and clinically indicated asymptomatic individuals with diagnostic-quality CTA images were included.

Exclusion Criteria

Participants with poor-quality or incomplete CT angiographic images due to motion artefacts, improper contrast opacification, or technical limitations were excluded. Patients with previous major intracranial vascular surgery, endovascular intervention, clipping or coiling of aneurysms, or extensive vascular distortion that prevented reliable assessment of normal arterial anatomy were excluded. Cases with severe traumatic vascular disruption, large intracranial masses markedly distorting the Circle of Willis, or inadequate visualization of the required vessels were also excluded.

Methodology: CT Angiography Technique: Cerebral CT angiography was performed according to the standard institutional CTA protocol using a multidetector CT scanner. Participants were positioned supine with the head adequately immobilized. A non-ionic iodinated contrast agent was administered intravenously using a power injector, followed by image acquisition during the arterial phase. Thin-section axial images were obtained from the skull base through the intracranial circulation. Images were reconstructed using multiplanar reconstruction, maximum-intensity projection, and three-dimensional volume-rendered techniques wherever required to provide detailed visualization of the intracranial arteries and their anatomical relationships.

Assessment of the Circle of Willis: The Circle of Willis was systematically evaluated for the anterior and posterior components. The vessels assessed included the bilateral anterior cerebral arteries (A1 segments), anterior communicating artery, terminal internal carotid arteries, posterior communicating arteries, and bilateral posterior cerebral arteries (P1 segments). The Circle of Willis was classified as complete or incomplete on the basis of visualization and continuity of its component vessels. Each arterial segment was evaluated for normal development, hypoplasia, aplasia, duplication, fenestration, asymmetry, or other identifiable anatomical variants.

Anatomical Parameters and Variations: The principal parameters recorded were completeness of

the Circle of Willis, type and location of anatomical variation, involvement of the anterior or posterior circulation, unilateral or bilateral occurrence, and the number of variants present in an individual participant. Variations such as hypoplastic or absent posterior communicating artery, hypoplastic or absent A1 segment, fetal-origin posterior cerebral artery, duplication or fenestration of vessels, and other uncommon vascular configurations were documented. Where measurable, vessel calibre and side-to-side asymmetry were also evaluated. Variants were categorized according to whether they involved the anterior circulation, posterior circulation, or both.

Associated Clinical and Radiological Findings:

Relevant associated CTA findings were recorded, including intracranial aneurysm, arterial stenosis or occlusion, cerebral infarction, vascular malformation, and other significant cerebrovascular abnormalities whenever present. The anatomical variants were correlated with the indication for CTA, clinical presentation, and associated vascular abnormalities. Particular attention was given to variations that could influence collateral cerebral circulation, interpretation of vascular imaging, endovascular procedures, aneurysm surgery, skull-base surgery, vascular bypass procedures, or operative planning in neurosurgical practice.

Image Interpretation and Data Collection: All CT angiographic images were reviewed systematically on a dedicated workstation using axial source images together with multiplanar and three-dimensional reconstructions. Each component of the Circle of Willis was assessed using predefined anatomical criteria. Findings were entered into a structured proforma containing demographic details, CTA indication, completeness of the Circle of Willis, specific vascular variations, laterality, associated cerebrovascular abnormalities, and potential clinical or neurosurgical relevance. In doubtful cases, images were reassessed before final categorization.

Statistical Analysis: The collected data were entered into Microsoft Excel and analyzed using IBM SPSS Statistics for Windows, Version 27.0. Continuous variables such as age and measurable vascular parameters were expressed as mean $\pm$ standard deviation or median with interquartile range according to data distribution, while categorical variables were presented as frequencies and percentages. The Shapiro-Wilk test was used to assess normality of continuous data. The Chi-square test or Fisher's exact test was applied to determine associations between categorical variables such as sex, completeness of the Circle of Willis, anatomical variants, and associated vascular abnormalities. Independent-samples t-test or Mann-Whitney U test was used for comparison of continuous variables where appropriate. A p-value <0.05 was considered statistically significant.

RESULTS

A total of 60 participants undergoing CT angiographic evaluation of the cerebral circulation were included in the study. Anatomical variations of the Circle of Willis were identified in 42 (70.00%) participants, whereas 18 (30.00%) participants showed no identifiable anatomical variation. The findings related to demographic characteristics, completeness of the Circle of Willis, specific anatomical variants, their distribution and laterality, and associated CT angiographic abnormalities are described below.

[Table 1] Demographic characteristics according to presence of anatomical variations in the Circle of Willis

The mean age of the overall study population was 47.18 ± 14.62 years. Participants with anatomical variations had a mean age of 49.10 ± 14.20 years, whereas those without anatomical variations had a mean age of 42.70 ± 13.60 years. The difference in mean age between the two groups was not statistically significant ($p=0.111$). With regard to age distribution, 10 (16.67%) participants belonged to the 18–30-year age group, of whom 5 (50.00%) had anatomical variations and 5 (50.00%) did not. Among 13 (21.67%) participants aged 31–40 years, anatomical variations were present in 8 (61.54%) and absent in 5 (38.46%). The 41–50-year age group comprised 15 (25.00%) participants, including 11 (73.33%) with variations and 4 (26.67%) without variations. Among 12 (20.00%) participants aged 51–60 years, 9 (75.00%) had anatomical variations and 3 (25.00%) had no variation. Of the 10 (16.67%) participants aged above 60 years, 9 (90.00%) showed anatomical variations and 1 (10.00%) showed no identifiable variation. The overall association between age group and anatomical variation was not statistically significant ($p=0.346$). Of the 60 participants, 35 (58.33%) were males and 25 (41.67%) were females. Among males, 25 (71.43%) had anatomical variations, while 10 (28.57%) had no variation. Among females, 17 (68.00%) demonstrated anatomical variations and 8 (32.00%) demonstrated no variation. There was no statistically significant association between sex and the presence of anatomical variations ($p=0.775$).

[Table 2] Completeness of the Circle of Willis and its components according to sex

A complete Circle of Willis was observed in 22 (36.67%) participants, while an incomplete Circle of Willis was identified in 38 (63.33%). Among 35 males, 11 (31.43%) had a complete Circle of Willis and 24 (68.57%) had an incomplete configuration. Among 25 females, 11 (44.00%) had a complete configuration and 14 (56.00%) had an incomplete configuration. The difference between males and females with regard to overall completeness of the Circle of Willis was not statistically significant ($p=0.319$). The anterior component of the Circle of Willis was complete in 49 (81.67%) participants and

incomplete in 11 (18.33%). Among males, the anterior component was complete in 28 (80.00%) and incomplete in 7 (20.00%). Among females, it was complete in 21 (84.00%) and incomplete in 4 (16.00%). No statistically significant sex-based difference was observed in the completeness of the anterior component ($p=0.693$). The posterior component was complete in 28 (46.67%) participants and incomplete in 32 (53.33%). Among males, 14 (40.00%) had a complete posterior component and 21 (60.00%) had an incomplete posterior component. Among females, 14 (56.00%) showed a complete posterior component, while 11 (44.00%) showed an incomplete posterior component. The difference between males and females was not statistically significant ($p=0.221$).

[Table 3] Frequency and pattern of specific anatomical variations identified on CT angiography

Of the total 60 participants, 18 (30.00%) showed no identifiable anatomical variation, whereas at least one anatomical variation was detected in 42 (70.00%) participants. Posterior communicating artery hypoplasia was identified in 17 (28.33%) participants and represented the most frequently recorded specific variation. Posterior communicating artery aplasia was observed in 9 (15.00%) participants, while fetal-origin posterior cerebral artery was identified in 8 (13.33%). A1 segment hypoplasia was observed in 6 (10.00%) participants, whereas A1 segment aplasia was detected in 3 (5.00%). Anterior communicating artery hypoplasia or aplasia was identified in 4 (6.67%) participants. Duplication of the anterior communicating artery was observed in 3 (5.00%) participants. Arterial fenestration was noted in 2 (3.33%) participants, while another uncommon anatomical variation was identified in 1 (1.67%) participant. Individual participants could demonstrate more than one anatomical variation; therefore, the frequencies of the individual variants were not mutually exclusive.

[Table 4] Distribution and laterality of anatomical variations among participants with variations

Among the 42 participants with anatomical variations, variations involving only the anterior circulation were observed in 10 (23.81%) participants, while posterior circulation-only variations were present in 24 (57.14%). Variations involving both the anterior and posterior circulations were identified in 8 (19.05%) participants. Among the 25 males with anatomical variations, anterior circulation-only involvement was present in 6 (24.00%), posterior circulation-only involvement in 14 (56.00%), and involvement of both circulations in 5 (20.00%). Among the 17 females with variations, anterior circulation-only involvement was observed in 4 (23.53%), posterior circulation-only involvement in 10 (58.82%), and involvement of both circulations in 3 (17.65%). The distribution of anatomical variations between the anterior and posterior circulations did not differ significantly according to sex ($p=0.978$). Regarding laterality, unilateral variations were identified in 25 (59.52%) of the 42

participants, bilateral variations in 11 (26.19%), and midline or non-lateral variations in 6 (14.29%). Among males with anatomical variations, unilateral involvement was observed in 15 (60.00%), bilateral involvement in 7 (28.00%), and midline/non-lateral involvement in 3 (12.00%). Among females, unilateral variations were present in 10 (58.82%), bilateral variations in 4 (23.53%), and midline/non-lateral variations in 3 (17.65%). The difference in laterality according to sex was not statistically significant ($p=0.858$).

[Table 5] Association between anatomical variations and associated CT angiographic abnormalities

Among the 42 participants with anatomical variations, intracranial aneurysm was identified in 8 (19.05%), compared with 1 (5.56%) of the 18 participants without anatomical variations. The difference was not statistically significant ($p=0.255$). Arterial stenosis or occlusion was observed in 13 (30.95%) participants with anatomical variations and in 2 (11.11%) participants without variations, with no statistically significant difference between the groups ($p=0.192$). Cerebral infarction or ischemic change was detected in 15 (35.71%) participants with anatomical variations and in 3 (16.67%) participants without anatomical variations. This difference was not statistically significant ($p=0.220$). Vascular malformation was identified in 3 (7.14%) participants with anatomical variations and in 1 (5.56%) participant without anatomical variations, with a p-value of 1.000. At least one clinically relevant CTA abnormality was present in 30 (71.43%) of the 42 participants with anatomical variations compared with 7 (38.89%) of the 18 participants without anatomical variations. This difference was

statistically significant ($p=0.023$). Conversely, no significant associated vascular abnormality was identified in 12 (28.57%) participants with anatomical variations and in 11 (61.11%) participants without variations, and this difference was also statistically significant ($p=0.023$).

[Table 6] Association of completeness of the Circle of Willis with clinically relevant CTA findings

Among the 38 participants with an incomplete Circle of Willis, intracranial aneurysm was identified in 7 (18.42%), whereas it was present in 2 (9.09%) of the 22 participants with a complete Circle of Willis. The difference between the two groups was not statistically significant ($p=0.464$). Arterial stenosis or occlusion was observed in 12 (31.58%) participants with an incomplete Circle of Willis and in 3 (13.64%) participants with a complete Circle of Willis. The difference did not reach statistical significance ($p=0.122$). Cerebral infarction or ischemic change was identified in 14 (36.84%) participants with an incomplete Circle of Willis compared with 4 (18.18%) participants with a complete Circle of Willis, with no statistically significant difference between the groups ($p=0.129$). At least one clinically relevant CTA abnormality was identified in 28 (73.68%) participants with an incomplete Circle of Willis compared with 9 (40.91%) participants with a complete Circle of Willis. The difference was statistically significant ($p=0.012$). In contrast, no significant associated abnormality was observed in 10 (26.32%) participants with an incomplete Circle of Willis and in 13 (59.09%) participants with a complete Circle of Willis, with a statistically significant difference between the two groups ($p=0.012$).

Table 1: Demographic characteristics according to presence of anatomical variations in the Circle of Willis

Characteristics	Total, n (%)	Variation present (n=42), n (%)	Variation absent (n=18), n (%)	p-value
Mean age (years), Mean $\pm$ SD	47.18 $\pm$ 14.62	49.10 $\pm$ 14.20	42.70 $\pm$ 13.60	0.111
18–30 years	10 (16.67%)	5 (50.00%)	5 (50.00%)	
31–40 years	13 (21.67%)	8 (61.54%)	5 (38.46%)	
41–50 years	15 (25.00%)	11 (73.33%)	4 (26.67%)	0.346
51–60 years	12 (20.00%)	9 (75.00%)	3 (25.00%)	
>60 years	10 (16.67%)	9 (90.00%)	1 (10.00%)	
Male	35 (58.33%)	25 (71.43%)	10 (28.57%)	0.775
Female	25 (41.67%)	17 (68.00%)	8 (32.00%)	

Table 2: Completeness of the Circle of Willis and its components according to sex

Anatomical configuration	Total, n (%)	Male (n=35), n (%)	Female (n=25), n (%)	p-value
Complete Circle of Willis	22 (36.67%)	11 (31.43%)	11 (44.00%)	0.319
Incomplete Circle of Willis	38 (63.33%)	24 (68.57%)	14 (56.00%)	
Complete anterior component	49 (81.67%)	28 (80.00%)	21 (84.00%)	0.693
Incomplete anterior component	11 (18.33%)	7 (20.00%)	4 (16.00%)	
Complete posterior component	28 (46.67%)	14 (40.00%)	14 (56.00%)	0.221
Incomplete posterior component	32 (53.33%)	21 (60.00%)	11 (44.00%)	

Table 3: Frequency and pattern of specific anatomical variations identified on CT angiography

Anatomical variation	Number of participants	Percentage (%)
No identifiable anatomical variation	18	30.00
At least one anatomical variation	42	70.00
Posterior communicating artery hypoplasia	17	28.33
Posterior communicating artery aplasia	9	15.00
Fetal-origin posterior cerebral artery	8	13.33
A1 segment hypoplasia	6	10.00
A1 segment aplasia	3	5.00

Anterior communicating artery hypoplasia/aplasia	4	6.67
Duplication of anterior communicating artery	3	5.00
Arterial fenestration	2	3.33
Other uncommon variations	1	1.67

Table 4: Distribution and laterality of anatomical variations among participants with variations (n=42)

Distribution of variation	Total, n (%)	Male (n=25), n (%)	Female (n=17), n (%)	p-value
Anterior circulation only	10 (23.81%)	6 (24.00%)	4 (23.53%)	0.978
Posterior circulation only	24 (57.14%)	14 (56.00%)	10 (58.82%)	
Both anterior and posterior circulation	8 (19.05%)	5 (20.00%)	3 (17.65%)	
Unilateral variation	25 (59.52%)	15 (60.00%)	10 (58.82%)	0.858
Bilateral variation	11 (26.19%)	7 (28.00%)	4 (23.53%)	
Midline/non-lateral variation	6 (14.29%)	3 (12.00%)	3 (17.65%)	

Table 5: Association between anatomical variations and associated CT angiographic abnormalities

Associated CTA finding	Variation present (n=42), n (%)	Variation absent (n=18), n (%)	p-value
Intracranial aneurysm	8 (19.05%)	1 (5.56%)	0.255
Arterial stenosis/occlusion	13 (30.95%)	2 (11.11%)	0.192
Cerebral infarction/ischemic change	15 (35.71%)	3 (16.67%)	0.220
Vascular malformation	3 (7.14%)	1 (5.56%)	1.000
At least one clinically relevant CTA abnormality	30 (71.43%)	7 (38.89%)	0.023
No significant associated vascular abnormality	12 (28.57%)	11 (61.11%)	0.023

Table 6: Association of completeness of the Circle of Willis with clinically relevant CTA findings

CTA finding	Incomplete Circle of Willis (n=38), n (%)	Complete Circle of Willis (n=22), n (%)	p-value
Intracranial aneurysm	7 (18.42%)	2 (9.09%)	0.464
Arterial stenosis/occlusion	12 (31.58%)	3 (13.64%)	0.122
Cerebral infarction/ischemic change	14 (36.84%)	4 (18.18%)	0.129
At least one clinically relevant CTA abnormality	28 (73.68%)	9 (40.91%)	0.012
No significant associated abnormality	10 (26.32%)	13 (59.09%)	0.012

DISCUSSION

The present study included 60 participants with a mean age of 47.18 ± 14.62 years. Participants with anatomical variations had a higher mean age of 49.10 ± 14.20 years compared with 42.70 ± 13.60 years among those without variations, although the difference was not statistically significant ($p=0.111$). The proportion with anatomical variations increased from 50.00% in the 18–30-year age group to 90.00% among participants aged >60 years, but the overall association with age group remained non-significant ($p=0.346$). Variations were also comparable between males (71.43%) and females (68.00%; $p=0.775$). Zaninovich et al. (2017), in a CTA-based analysis of 834 individuals, reported an overall complete Circle of Willis in 37.1% and demonstrated a progressive reduction in completeness with increasing age. Completeness among men decreased from 47.0% in the youngest group to 29.4% and 18.8% in progressively older groups, while corresponding frequencies among women were 59.1%, 44.2%, and 30.9%. They also observed greater overall completeness in females than males (43.8% versus 31.2%). Thus, the increasing frequency of anatomical variations with advancing age in the present study followed a similar age-related pattern, although the present sex difference was small and statistically non-significant.^[7] A complete Circle of Willis was demonstrated in 22 (36.67%) participants in the present study, whereas 38 (63.33%) had an

incomplete circle. The anterior component was complete in 49 (81.67%) and incomplete in 11 (18.33%), while the posterior component was complete in only 28 (46.67%) and incomplete in 32 (53.33%). The complete configuration was observed in 31.43% of males and 44.00% of females, although this difference was not significant ($p=0.319$). Coulier (2021) evaluated CTA reconstructions from 511 patients and identified a completely formed cerebral arterial circle in 115 (22.58%) patients, while another 157 (28.6%) had a nearly complete configuration with only one missing segment. The anterior arch was incomplete in 18.4%, which was almost identical to the 18.33% recorded in the present study. In contrast, the posterior arch was incomplete in 73.18% of Coulier's series compared with 53.33% in the present study. In both studies, therefore, incomplete configurations were substantially more frequent in the posterior than in the anterior component, principally reflecting greater variability of the posterior communicating arterial system.^[8] Anatomical variation in at least one component of the Circle of Willis was detected in 42 (70.00%) participants in the present study. Posterior communicating artery hypoplasia was the most frequent individual variation, occurring in 17 (28.33%), followed by posterior communicating artery aplasia in 9 (15.00%), fetal-origin posterior cerebral artery in 8 (13.33%), A1 segment hypoplasia in 6 (10.00%), anterior communicating artery hypoplasia/aplasia in 4 (6.67%), and A1 segment

aplasia in 3 (5.00%). Dhakal et al. (2020), in a CT cerebral angiography study of 95 patients, found Circle of Willis variations in 52 (54.7%) subjects, a somewhat lower frequency than the 70.00% observed in the present study. Their most frequent variation was similarly hypoplasia of the posterior communicating artery, detected in 33 (34.7%) patients. They reported posterior communicating artery aplasia in 7.4%, fetal-origin posterior cerebral artery in 8.4%, and hypoplastic A1 segment in 4.2%. Therefore, although the absolute frequencies of several individual abnormalities were higher in the present series, both studies identified the posterior communicating artery as one of the principal sites of anatomical variation on CTA.^[9]

Among the 42 participants with anatomical variations in the present study, posterior circulation-only variants accounted for 24 (57.14%), anterior circulation-only variants for 10 (23.81%), and combined anterior and posterior variations for 8 (19.05%). The pattern was essentially similar in males and females ($p=0.978$). Furthermore, 25 (59.52%) variations were unilateral, 11 (26.19%) bilateral, and 6 (14.29%) midline or non-lateral, with no significant sex-related difference in laterality ($p=0.858$). De Caro et al. (2021) evaluated 1,131 patients with acute ischemic stroke and identified one or more Circle of Willis variants in 702 (62.1%), compared with 54.8% among 562 matched controls ($p<0.01$). Among the 702 stroke patients with variants, 384 (54.7%) had posterior circulation-only variants, 165 (23.5%) had anterior circulation-only variants, and 153 (21.8%) had abnormalities involving both circulations. These proportions closely resembled the respective 57.14%, 23.81%, and 19.05% found in the present study. Their most frequent posterior individual variant was also unilateral fetal-type PCA in 137/1,131 (12.11%), supporting the predominance of posterior and frequently unilateral vascular configurations observed in the present series.^[10] In the present study, intracranial aneurysm was detected in 8 (19.05%) participants with anatomical variations compared with 1 (5.56%) without variations, although this difference was not statistically significant ($p=0.255$). Vascular malformations were found in 3 (7.14%) participants with variants and 1 (5.56%) without variants ($p=1.000$). Machasio et al. (2019), in a cerebral CTA study involving 94 patients, reported intracranial aneurysms in 24.5% and arteriovenous malformations in 8.5%. Their frequency of vascular malformations was therefore close to the 7.14% observed among participants with Circle of Willis variants in the present study. Although aneurysms were more frequent in the variant group in the present study, the association was not statistically significant. Similarly, Machasio et al. found no significant association between Circle of Willis configuration and the occurrence of aneurysms or arteriovenous malformations. Their study additionally reported anterior communicating artery aneurysms as the commonest aneurysm group, constituting 43.6% of

detected aneurysms.^[11] Arterial stenosis or occlusion was identified in 13 (30.95%) participants with anatomical variations in the present study compared with 2 (11.11%) participants without variations. Although this represented an appreciable numerical difference, statistical significance was not reached ($p=0.192$). Waaijer et al. (2007) compared 91 patients with symptomatic carotid artery stenosis with 91 control subjects using multidetector CTA. Hypoplastic A1 segments were identified in 16 patients with carotid stenosis compared with 4 controls, while non-visualized A1 segments were found in 14 patients compared with only 1 control ($p<0.01$). An isolated compromised anterior collateral pathway occurred in 9% of patients versus 1% of controls, and combined compromise of the anterior and posterior pathways was observed in 26% versus 4%, respectively ($p<0.01$). The higher proportion of stenosis or occlusion among participants with variants in the present study showed a similar numerical direction, although its smaller sample did not demonstrate a statistically significant association.^[12] Cerebral infarction or ischemic change was recorded in 15 (35.71%) participants with anatomical variations compared with 3 (16.67%) without variations in the present study ($p=0.220$). When Circle of Willis completeness itself was considered, ischemic change was found in 14 (36.84%) participants with an incomplete circle and 4 (18.18%) with a complete circle ($p=0.129$). Varga et al. (2019) examined 544 patients undergoing carotid endarterectomy and 196 controls using CT and multidetector CTA. Circle of Willis variants were present in 97% and a compromised circle in 81% of the carotid endarterectomy cohort. Cerebral ischemic lesions were found in 146/544 (27%) patients overall, but the prevalence increased to 35% among subjects with a severely compromised Circle of Willis compared with 23% in the remaining configuration groups, producing a significant association ($p=0.002$). They also observed that ICA stenosis $\geq 90\%$ was significantly associated with ipsilateral A1 hypoplasia or non-visualization ($p<0.001$). The higher proportion of ischemic changes in the variant and incomplete groups in the present study therefore showed a direction similar to that reported by Varga et al., despite not reaching statistical significance for the individual ischemic endpoint.^[13] When clinically relevant CTA abnormalities were considered collectively in the present study, at least one abnormality was identified in 30 (71.43%) participants with anatomical variations compared with 7 (38.89%) without variations, a statistically significant difference ($p=0.023$). Similarly, 28 (73.68%) participants with an incomplete Circle of Willis had at least one clinically relevant CTA abnormality compared with 9 (40.91%) participants with a complete Circle of Willis ($p=0.012$). Banga et al. (2018) demonstrated the clinical relevance of compromised Circle of Willis collateral anatomy in 545 patients undergoing carotid eversion endarterectomy without routine

shunting. A complete Circle of Willis was present in only 19 (3.5%), while an isolated middle cerebral artery configuration was detected in 34 (6.3%). Immediate neurological events occurred in only 4 of 330 patients (1.2%) when at least one collateral pathway was complete, compared with 8 of 34 patients (24%) with an isolated middle cerebral artery configuration. The latter configuration was independently associated with neurological events with an odds ratio of 11.12 (95% CI 3.57–35.87; $p < 0.001$). Although the clinical populations and outcomes differed, these findings complement the present observation that incomplete or variant Circle of Willis anatomy was associated with a greater overall burden of clinically relevant CTA abnormalities and emphasize the importance of defining collateral anatomy during neurovascular and neurosurgical assessment.^[14]

CONCLUSION

Anatomical variations of the Circle of Willis were common on CT angiography, with incomplete configurations occurring more frequently than complete configurations. Posterior circulation variations, particularly involving the posterior communicating artery, were the predominant abnormalities. Clinically relevant CTA abnormalities were significantly more frequent in participants with anatomical variations and in those with an incomplete Circle of Willis. Detailed preoperative and radiological assessment of these vascular variants may assist in cerebrovascular evaluation, collateral circulation assessment, and neurosurgical planning.

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