Magnetic resonance angiographic evaluation of circle of Willis: A morphologic study in a tertiary hospital set up

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Abstract

Background: Anatomy of circle of Willis (CW) shows wide variation in different individuals, population groups, and has vital clinical significance in causation and presentation of clinical disease. This study evaluates the anatomical variations, incidence of various common anomalies of CW in south Indian tertiary hospital set up, using three-dimensional time-of-flight (3D-TOF) magnetic resonance angiography (MRA). **Materials and Methods:** A total of 300 patients referred for neuroimaging study over a period of 2-year were included in the analysis. In this prospective and retrospective study, 198 men and 102 women; mean age, 55 years) underwent 3D-TOF MR angiograms of the CW using a 1.5-tesla MR scanner. Images were reviewed for anatomical configuration of the CW using maximum intensity projection (MIP) and 3D volume rendered images. **Results:** On analysis, a complete CW was seen in 50 (16.6%) of 300 subjects. An incomplete anterior and posterior CW was found in 66 (22%) The remaining 184 (61.3%) subjects had partially complete CW configuration. The most common type of CW in a single subject was anterior variant type A and posterior type variant E. **Conclusion:** We observed wide variation in CW configuration in our patients. The prevalence of complete configuration of the circle is 16.6%; slightly higher in females and younger subjects. Complete anterior circle was present in 77.3%. Most common anterior variant is type A (normal anterior configuration) with a prevalence of 66%. The most common posterior circle variant is type E (hypoplasia or absence of both PcomA) with 32.6%. Overall, CW variants are slightly more common among the women in comparison to men. Incidence of associated anomalies like aneurysm or arteriovenous malformation (AVM) was comparable to that described in literature.

Key Words

Anatomy CW, circle of Willis, CW, configuration CW, MRI

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Introduction

Vascular anatomy of CW had been subject of extensive autopsy studies as well as *in vivo* imaging studies.(1-8)CW is constituted by two internal carotid arteries (ICAs) and basilar artery anastomosing at the base of the brain. The carotid arteries and their branches supply the anterior portion of the brain referred to as the anterior circulation. Whereas, posterior circulation refers to vertebrobasilar system that supplies the posterior portion of the brain. The anterior communicating arteries (A com As) and posterior communicating arteries (PcomAs) are component vessels of the CW and designated as the primary collateral pathways. Other pathways, known as the secondary collateral pathways, may also be recruited. Examples include flow reversal through the ophthalmic arteries, reversed flow through the anterior choroidal artery, and anastomosis between the cortical branches of the intracerebral arteries (leptomeningeal collaterals). The collateral potential of the CW is believed to be dependent on the presence and size of its component vessels,[1-3] which vary among normal individuals.[3-10]

Considerable anatomic variation exists in the CW. Recent cadaveric study has shown 21 types of CW variations.[9] Classification presented in the work of Chen *et al.*,[11] is adopted in our presentation for the simplicity of the scheme. There are 10 types of variations (A–J) in anterior and posterior circle which are illustrated in the figures [Figures 1 and 2]. One common variation consists of relative narrowing of proximal part of the posterior cerebral artery (PCA) with large ipsilateral PcomA, so the ICA supplies the posterior cerebrum. In another variation, the AcomA is a large vessel, such that a single internal carotid supplies both the anterior cerebral arteries (ACAs). In third variation, ACA gives rise to both post-communicating segments and supplies retrograde flow to the ipsilateral

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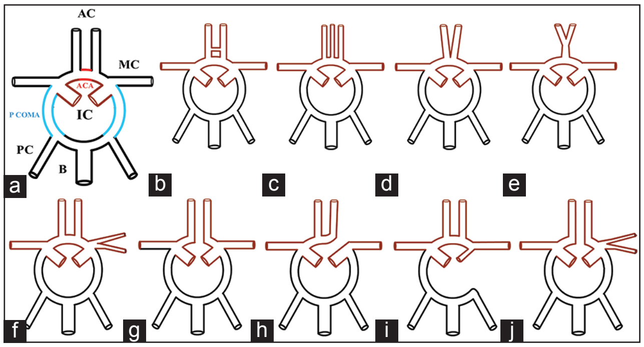


Figure 1: (a) Schematic diagrams of anatomic variations in the anterior part of the CW (modified from Chen *et al.*[11]). (a) Normal adult pattern. There is a single AcomA (red). The ICA bifurcates into the pre-communicating segment of the ACA and the MCA. (b) Two or more AcomAs. (c) Median artery of the corpus callosum arises from the AcomA. (d) Fusion of the ACAs over a short distance. (e) ACA forms a common trunk and split distally into two post communicating segments. (b) (f) MCA originates from the ICA as two separate trunks. (g) Hypoplasia or absence of an AcomA. (h) One pre-communicating segment of an ACA is hypoplastic or absent, the other pre-communicating segment gives rise to both post-communicating segments of the ACAs. (i) Hypoplasia or absence of an ICA. ACA gives rise to both postcommunicating segments, supplies retrograde flow to the ipsilateral precommunicating segment. (j) Hypoplasia or absence of an anterior communication. The MCA arises as two separate trunks. CW = Circle of willis, ICA = Internal carotid artery, MCA = Middle cerebral artery, AcomA = Anterior communicating artery, ACA = Anterior cerebral artery

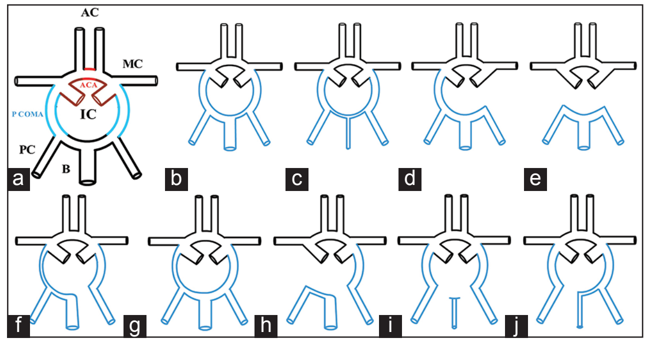


Figure 2: (a) Schematic diagrams of anatomical variations of the posterior part of the CW (modified from Chen *et al.*[11]). (a) Bilateral PcomAs are present (blue). (b) PCA originates predominantly from the ICA. This variant is known as a unilateral fetal type PCA; the PcomA on the other side is patent. (c) Bilateral fetal type PCAs with both pre-communicating segments of the PCAs patent. (d) Unilateral PcomA present. (e) Hypoplasia or absence of both PcomAs and isolation of the anterior and posterior parts of the circle at this level. (b) (f) Unilateral fetal type PCA and hypoplasia or absence of the pre-communicating segment of the PCA. (g) Unilateral fetal type PCA and hypoplasia or absence of the contralateral PcomA. (h) Unilateral fetal type PCA and hypoplasia or absence of both pre-communicating segment of the PCA and the PcomA. (i) Bilateral fetal type PCAs with hypoplasia or absence of bothpre-communicating segments of the PCAs. (j) Bilateral fetal type PCAs with hypoplasia or absence of the pre-communicating segment of either PCA. PCA = Posterior cerebral artery, PcomA = Posterior communicating artery

pre-communicating segment, which, in turn, gives rise to the ipsilateral middle cerebral artery (MCA; both ACAs and both MCAs are supplied by a single ICA). Physiologically, arrangement of the cerebral arteries in the CW creates deficiencies, redundancies; also provide potential collateral pathways in cerebral circulation. If one part of the circle becomes blocked or narrowed, blood flow from the other arteries can preserve the cerebral perfusion by maintaining enough flow to avoid ischemia.

The CW is an important potential collateral pathway in maintaining adequate cerebral blood flow in patients with ICA obstruction. With the advances in microneurosurgery and the more effective ability to deal with occlusive neurovascular disease surgically and by interventional methods, the accurate knowledge of the intracranial vascular anatomy has become increasingly important.

Based on anatomical[12-14] and radiological studies,[7,15,16] it has been shown that more than half of healthy subjects have anatomical variations in the CW. Recent studies have investigated the role of the CW in the development of collateral flow in ICA obstruction; these studies were based on mathematical models[17-19] and used transcranial Doppler ultrasound,[20-25] digital contrast–enhanced angiography,[3,26] or magnetic resonance angiography (MRA).[2,3,27-29] MRA has previously been shown to be well-suited to investigate the CW, in view of the fact that it is able to provide morphological as well as hemodynamic information concerning blood flow direction in individual vessels accurately.[30,31] Previous studies have demonstrated that three-dimensional time-of-flight (3D-TOF) MRA is a sensitive, noninvasive modality suitable for detecting the anatomy of the CW in healthy volunteers and patients with carotid artery disease.[11,32]

Aims and objectives

The purpose of this study is to evaluate and to describe the prevalence and pattern of CW, arterial variants (aplasia, hypoplasia) and anomalies (arteriovenous malformations (AVMs) and aneurysms) in noncontrast 3D-TOF-MRA in the study group. In addition to providing a standard of reference for future research on the circle with 3D TOF MRA, the purpose of this study was to investigate whether any age- or sex-related differences could be found in circle morphology.

Materials and Methods

In a prospective and retrospective observational study, 300 patients referred for neuroischemic study protocol from February 2010 to July 2011 were included in the study. Study was approved by the institutional review board. Informed consent from the patient or guardian was obtained before scanning. All patients (198 men and 102 women; mean age, 55 years) underwent 3D-TOF MR angiograms of the CW. Images were obtained with the sequence of spoiled gradient-recalled acquisition (SPGR) using a 1.5-tesla MR scanner (Achieva; Philips Medical Systems, The Netherlands). Patients with pacemaker, ferromagnetic intracerebral aneurysm clips, or other metallic implants and patients with claustrophobia were excluded. Severely ill, uncooperative patients who were not able to remain stable for study duration were also excluded. Images were reviewed for CW anatomy and configuration.

Scanning technique: Patients were imaged in supine position, wherever necessary, after sedation with midazolam 0.07-0.08 mg/kg intramuscular (IM; approximately 5 mg IM) administered up to 1 h before the study in uncooperative patients. Examination was done with a dedicated head coil. Monitoring of vital signs of patient was performed throughout the scanning. Dedicated, optimized high-resolution 3D-TOF MRA protocol with repetition time (TR)/echo time (TE)/flip angle of 19/5.7 ms/16°, respectively, with isotropic resolution of 0.6 × 0.6 × 0.6 mm^3 was used. T1-weighted volume scans and T2-weighted multisection fast-field echo anatomic scans were obtained for the detection of brain abnormalities. Scanning parameters included; slice thickness 1.2 mm, 0.6 mm slice overlap, field of view of 100 × 100 mm, and matrix 0.6 × 0.6 × 0.6 mm^3 andTR-19 ms, TE - 5.7ms, and flip angle-16°. Totally 50 slices covering a volume of 30 mm (50 × 0.6 mm effective slice thickness) was obtained. The total imaging time was approximately 15 min, of which the 3D TOF MRA sequence required 3 min 24 s. These axial source images were post-processed by the maximumintensity projection (MIP) algorithm [Figure 3a] to produce eight projections rotating about the section axis. All component vessels of the CW were assessed by measuring the diameter on the individual MIP images. Whenever there was doubt in determining the diameter of vessel due to overlap in the MIP images, the TOF source images were then reviewed on the advanced workstation (Philips ADW 4.0 workstation). Occasionally, it was necessary to cutoff the unwanted branching vessel on the images in order to betterdepict the target vessels and assess correct diameter. Vessels visualized as continuous segments of at least 0.8 mm in diameter, were considered present. Those smaller than 0.8 mm in diameter were considered as hypoplastic.[11,33] The images were also reviewed with volume rendering technique and evaluated in all the angles [Figure 3b]. Arteries when seen as noncontinuous segments were considered as absent. The anterior and posterior parts of CW were evaluated separately and classified according to the scheme. The prevalence of each anatomic variant was documented.

Results

Study group consisted of 300participants (198 men and 102 women; mean age, 55 years) [Graph 1a and b]. Incidence of various types of CW is documented in Table 1. Common morphological types of CW variations [Table 2] and common types of anterior and posterior circulation are illustrated in Table 3. The prevalence of the variants of the anterior and posterior circle of Willis (CW) for different age groups of both sexes and for total subjects are also shown in Graph 2. Variant type A [Figure 4a] was the most common type of anterior part of the CW in all age groups and sexes [Table 2 and Graph 2a and b].

Anterior CW variants

The anterior CW was complete in 232 out of 300 participants (77.3%), with a normal configuration (Type A) seen in 198 subjects. In two patients, two AcomAs [Figure 4b] were observed. The anterior circle was incomplete in 67 participants who had compromised anterior collateral flow, AcomA was absent in 39 [Figure 4c1 and 2]. The remaining 28 subjects had A1 hypoplasia or aplasia [Figure 5g and h]. The most common type of anterior collateral was type A [Figure 4a1 and 2], in which all component vessels were competent.

Posterior circle variants

The prevalence of the variants of the posterior part of CW was shown for different age groups and both sexes in Table 2. The prevalence of unilateral fetal-type posterior communicating artery (FTP com A; posterior part variants B, F, G and H) was 16% and bilateral FTP com A (posterior part variants C, I, and J) was found in 7%. A higher percentage of incomplete collaterals were observed in the posterior part of the circle compared with the anterior collaterals. An adult configuration complete posterior circles [Figure 6a] was observed in 51 participants, and transitional variant [Figure 6b and c] was observed in 29 participants. A FTP CW was seen in 69 (23%) of the 300 subjects. Of the 69 subjects with FTP, 56 (18.6%) were classified as having partial FTP [Figures 6b and c, 7g, 8j] in which a hypoplastic P1 segment was present, and 13 (4.3%) were found to have a full FTP in which a P1 segment was

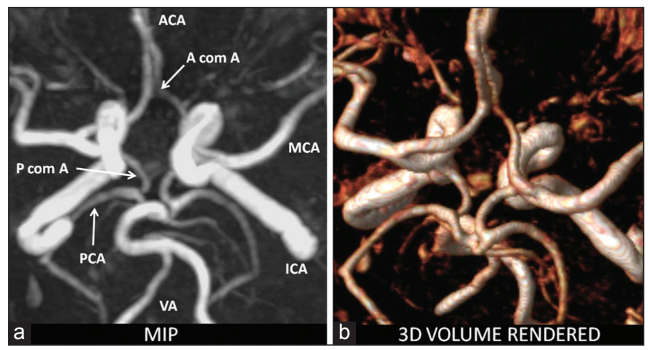
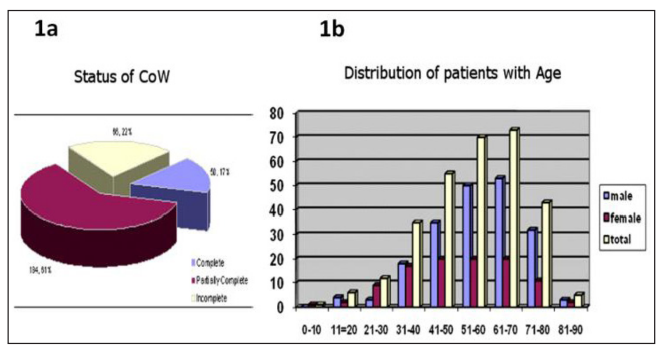
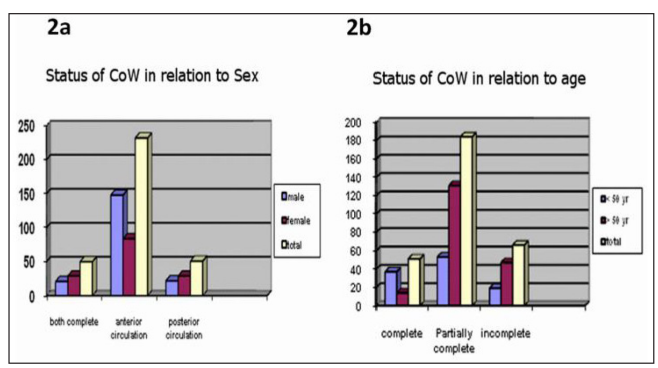


Figure 3: Maximum intensity projection (MIP) and volume rendered (VR) three-dimensional time-of-flight magnetic resonance (MR) angiogram of the normal CW



Graph 1: Status of circle of Willis and age distribution of patients



Graph 2: Status of the circle of Willis in relation to sex and age

absent [Figures 7f and 8h]. The most common type of posterior variation was type E [Figure 7e], in which bilateral P com A were absent. Of the 56 participants with a partial FTP, a unilateral FTP was found in 35 participants and bilateral FTP was seen in 21 participants.

Table 1: COW. Types of anterior and posterior circulation and relative incidence

Morphological types of COW in relation to Sex (%)						
	Anterior circulation			Posterior circulation		
Types	TOTAL	M	F	TOTAL	M	F
A	66	42.3	23.6	17	7.3	9.7
B	0.6	0.3	0.3	4.67	3.7	1
C	2	1	1	4.3	2.3	2
D	6	4	2	9	7.3	1.6
E	2.6	1.6	1	32.7	23	9.7
F	0	0	0	1	0.7	0.3
G	11.6	12	4	7	6.3	0.66
H	9.3	9	2	3.3	1.6	1.6
I	0	0	0	0	0	0
J	0	0	0	2.6	2.3	0.3

Table 2: Morphology and incidence of variation of COW

Morphology of circle of Willis		
Morphology	Cases	Percentage
Complete circle	50	16.6
Incomplete ant, post circle	66	22
Partially complete	184	61.4
Complete anterior circle	232	77.3
Complete posterior circle	99	33
Isolation		
Isolation of contralateral (Ant J)	0	0
Isolation of posterior circulation (Post G)	98	32.6

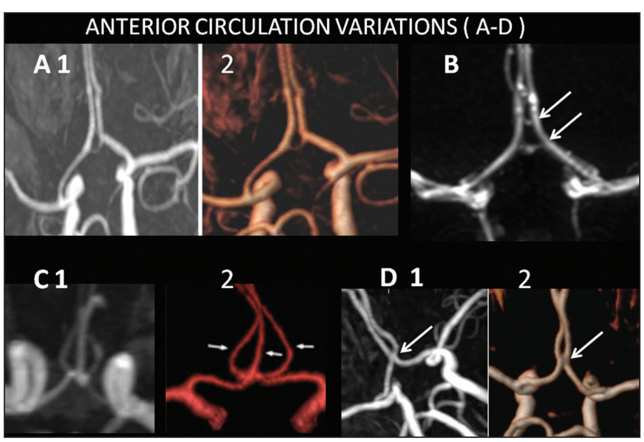


Figure 4: Type A: A 40 year-old male with syncope, suspected of cerebrovascular accident (CVA): A single AcomA. The ICA bifurcates into the pre-communicating segment of the ACA and the MCA. Type B: A 48 year-old male with syncope, suspected of CVA: Two AcomAs (arrows). (c1 and 2) Type C: A 42-year-old male with transient unsteadiness, suspected of CVA: Medial artery of the corpus callosum arises (arrow) from the AcomA. (d1 and 2) Type D: A 36-year-old female with headache, for exclusion of vascular lesion: Focal fusion of the ACA (long arrow)

Entire circle

Table 1 and Figures 4 and 5 shows the prevalence of complete, partially complete, and incomplete configuration of the entire CW for different age groups, both sexes, and total subjects. There was statistically significant difference among different age and sex groups. Higher prevalence of complete CW was found in younger group (below 50 years; 33.9% of younger older subjects versus 6.8% of older subjects) and in females (28.4% of women versus 10.6% of men).

Combined analysis of entire circle

In the combined analysis, a complete CW was seen in 50 (16.6%) of 300 subjects. An incomplete anterior and posterior CW was found in 66 (22%) of 300 subjects. The remaining 184 (61.3%) subjects had partially complete CW configuration. The most common type of CW in a single subject was anterior variant type A and posterior type variant E. Incidentally three patients had aneurysms, one subject was having AVM and another subject was having persistent trigeminal artery on MR angiograms [Figure 9].

Discussion

The configuration of the CW has been investigated in many anatomical and clinical studies.[3-10] There are only a few studies that have systematically investigated the configuration of the CW in a general population.[9,10] There is a great clinical significance to CW variations, allowing prognostication of intracranial ischemia in incomplete circles.

MRA has demonstrated high sensitivity in evaluation of component vessels in the CW.[29] Though well-accepted clinically, sensitivity of 3D time-of-flight (TOF) MRA depends on the blood flow velocity of the vessel, and the technique may have difficulties in visualizing small vessels in the CW with slow or turbulent flow.[34] In most studies, MRA 3D acquisitions

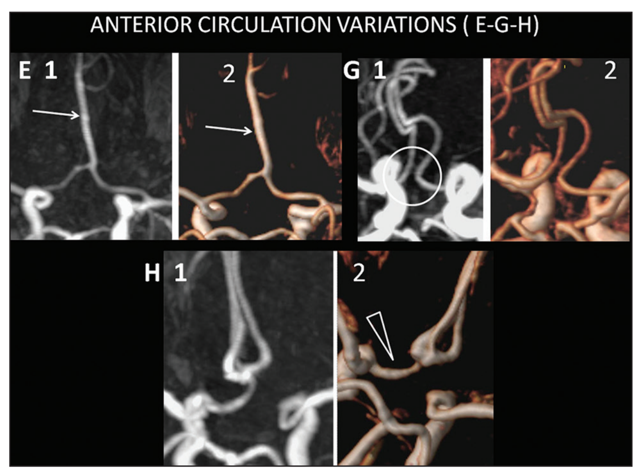


Figure 5: (e1 and 2) Type E: A 24-year-old female with migraine, for exclusion of vascular lesion: ACA forms a common trunk (arrow) and split distally into two post-communicating segments. (g1 and 2) Type G: A 52-year-old male with transient visual disturbance, suspected of CVA hypoplasia or absence of an AcomA (circle). (h1 and 2) Type H: A 53-year-old male with two episodes of gait unsteadiness, suspected of CVA: One pre-communicating segment of an ACA is hypoplastic or absent and the other pre-communicating segment (triangle) gives rise to both post-communicating segments of the ACAs

Table 3: COW common variations and incidence

Common types of variations			
Circulation	**Type**	**No**	**Percentage**
Anterior	Type A	198	66
	Type G	35	12
	Type H	28	9
Posterior	Type E	98	32.6
	Type A	51	17
	Type D	27	9

were made with either steady state precession (FSSP) or spoiled gradient technique (SPGR) using 1.5-tesla systems. Using FSSP technique, an axial slab with a thickness of 52 mm and 64 partitions was placed over the entire CW. A gradient-echo sequence (fast imaging with steady-state precession) with a matrix of 256 3 512 and a field of view of 200 mm was used, which yields a voxel size of 0.78 3 0.39 3 0.81 mm^3 acquisition time of 11 min 47 s.[30] Typical parameter used in SPGR technique were 45 ms TR, 4.9 ms TE, 20° flip angle, 256 × 192 matrix in a 14 cm field of view, and 42 mm slab with 60 serial axial slices of 0.7 mm thick with total imaging time of 10 min.[11]

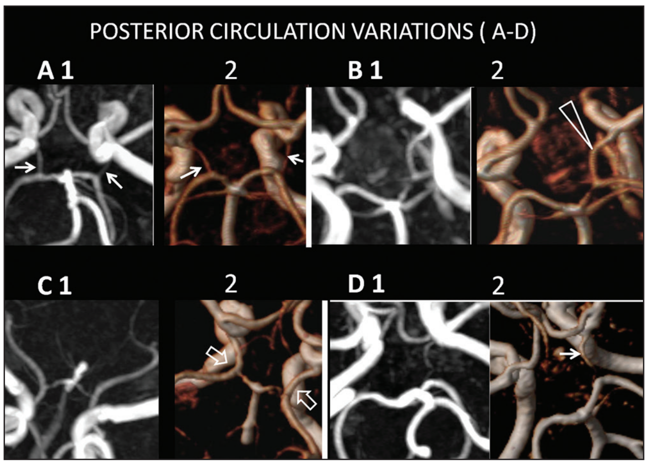


Figure 6: (a1 and 2) Type A: A 52-year-old male with episodes of blurred vision, suspected with CVA; bilateral PcomAs are present (arrows). (b1 and 2) Type B: A 62-year-old male with a syncopal attack, suspected with CVA: PCA originates predominantly from the ICA (triangle). This variant is known as a unilateral fetal type PCA; the PcomA on the other side is patent. (c1 and 2) Type C: A 24-year-old female with migraine, referred to exclude intracranial vascular abnormality: Bilateral fetal type PCAs with both pre-communicating segments of the PCAs patent (arrow heads). (d1 and 2) Type D: A 55-year-old male with transient right hemiparesis, suspected with CVA. Unilateral PcomA present (arrow)

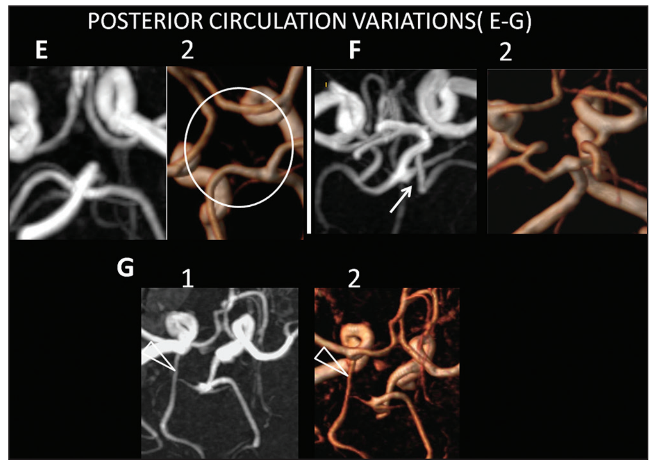


Figure 7: (e1 and 2) Type E: A 65-year-old male with transient visual blurring, suspected with CVA. Hypoplasia or absence of both PcomAs and isolation of the anterior and posterior parts of the circle at this level (circle). (f1 and 2) Type F: A 55-year-old male with transient right hemiparesis, suspected with CVA. A 59-year-old female with recurrent vertigo, suspected with CVA. Unilateral fetal type PCA and hypoplasia or absence of the pre-communicating segment of the PCA (arrow). (g1 and 2) Type G: A 35-year-old male with sudden onset unsteady gait, suspected with CVA. Unilateral fetal type PCA (triangle) and hypoplasia or absence of the contralateral PcomA

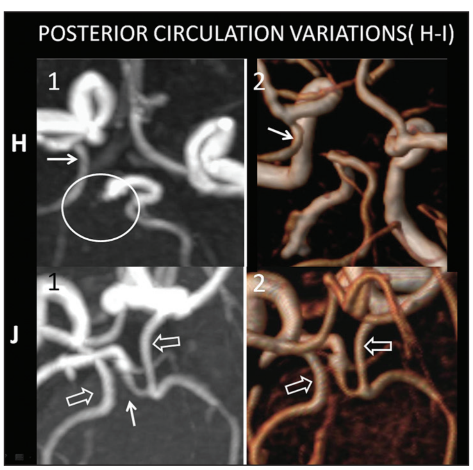


Figure 8: (h1 and 2) Type H: A 48-year-old female with headache, visual blurring, suspected with CVA. Unilateral fetal type PCA (arrow) and hypoplasia or absence of both pre-communicating segment of the PCA and the Pcom A (circle). (i1 and 2) Type I: A 51-year-old female with migraine, referred for exclusion of vascular intracranial lesion. Bilateral fetal type PCAs (open arrow) with hypoplasia or absence of the pre-communicating segment of either PCA (arrow)

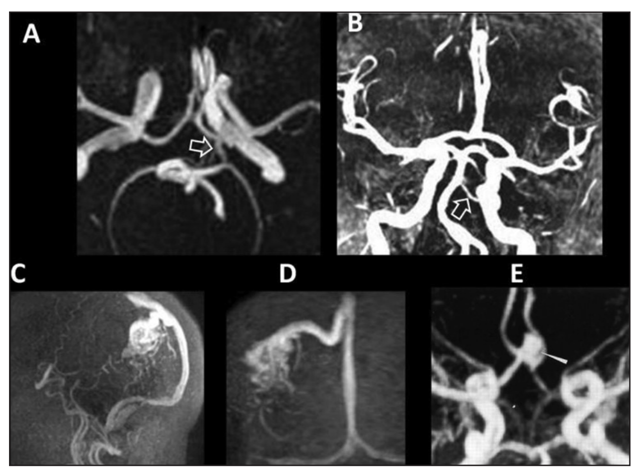


Figure 9: (a and b) A 50-year-old male with syncope, suspected of CVA: Persistent left trigeminal artery (arrow). (c and d) A 47-year-old female with recurrent headache, suspected of intracranial vascular lesion: AVM in right parietooccipital region in right PCA territory draining into right cortical veins and into superior sagittal sinus. (e) A 55-year-old male with transient gait disturbance, suspected of CVA: AcomA aneurysm (pointer)

Our study focuses on anatomical variants of the CW. In the evaluation process, like in earlier studies, we have considered the following vessels forming part of the CW: The A com A, the pre-communicating segment (A1) of the ACA, the pre-communicating segment (P1) of the PCA, the P com A, and ICA. CW configuration can be categorized in to three different types based on the structure of P1, P2 segment of PCA, and P Com A. Configurations are the adult type, transitional type, and fetal type. In adult configuration, P1 diameter is larger than the PComA diameter. In transitional configuration, diameters of both arteries are equal and equally contribute in formation of P2 of PCA. Fetal or embryonic configuration diameter of the P1 is smaller than diameter of P Com A and P2.[9] In previous studies, the prevalence of a complete anterior circle varied from 74 to 90% in different ethnic groups,[9,35-37] almost similar to our observation. Autopsy studies, however, showed lower incidence of complete circles.[36] One recent cadaveric study has reported variation of CW in 40% with maximum variation in Pcom A (50%) followed by A com A (40%).[9] In the present study, the prevalence of entirely complete CW was 16.6%, higher in females than males (28.4 and 10.6%, respectively) and young than older subjects (33.9 and 6.8%, respectively). Previous studies have shown higher incidence of complete circles in female patients and younger patients.[11,33,37] Diameter of the proximal arteries measured on MRA in control studies tend to be larger in male show tendency to decrease with age. Our observation is similar to earlier studies. Additionally, average age of male subjects was 63 years and that of the female 47 years, which might partly explain higher visualization in female subjects. The most common variant in anterior circulation is type A, which is normal pattern in both the sexes. Type A variant in anterior circulation in common among women (n = 71, 69.6%) slightly more frequent compared to men (n = 127, 64.1%). Type E variant of posterior circulation is most common in both the sexes. It is also common in men (n = 69, 34.8%), slightly more compared to women (n = 29, 28.4%).

In a large study of Indian subcontinental patients, Kapoor *et al*.,[14] observed that 45.2% conformed to the typical pattern. In the rest of the study group there were variations. In other studies, complete CW was observed in 4.6-72.2%.[10,37] The major variation is observed in incidence of complete CW, in autopsy studies, ranging from 14.2 to 52.3%;[36] relatively lower than clinical observation. Several reasons could account for this variation; first, the subject selection difference, healthy volunteers were included in some studies with additional subjects without vascular disorders or even some with neurological disease.[28,38] Second reason could be due to the difference in observation method, like studies wherein phase-contrasted MR angiography was utilized in addition to TOF study.[28] Third reason is related to the criteria set for what constitutes a complete-circled configuration. We applied the criterion of the vessel diameter less than 0.8 mm as absence in determining the prevalence of various anatomical variants. Some autopsy studies used 1 mm as their lower limit.[16,36] Although TOF-MRA demonstrates high sensitivity in detecting intracranial arteries, this technique has its disadvantages. Slow or turbulent flow may not be demonstrated in the TOF-MRA images, even though the vessels are patent. Therefore, the prevalence of the complete configuration of circle may be underestimated. The incidence of incomplete configuration of the circle is 22%. Among these variations, a single major ICA supplying several cerebral arterial territories, with little collateral flow provided by other arteries, should be taken note carefully. Such variation, called isolated circulation, is an important observation for preoperative surgical planning; especially when temporary or permanent occlusion of the parent artery is anticipated. In such instance, temporary occlusion of the ICA during carotid endarterectomy would lead to the risk of ischemic insult in the watershed area between these separately perfused territories.

Reasons for variations in the segments of the CW have been hypothesized. Genetic factors[10] and postnatal development of the brain following occlusive diseases[39] are main theories. From the evolutionary standpoint, it is noteworthy that variations of the cerebral arteries seem to be equally common in humans as well as animals.[40]

We noted transitional-type posterior circles in our population, with an incidence of 4%. Interestingly, we also observed higher occurrence of posterior variant (variant J) in the study population. We believe that, these observed variants call for need of larger population-based studies to improve our understanding of regional variations.

In a large study involving north Indian subject groups, intracranial saccular aneurysm was present in 1%[14] and AVMs in 1.4% in the PCA. In our study, aneurysms were detected in 1%; noted in both the A com A and the left ACA. AVMs were found in a single case (0.33%) in the right parietooccipital region. Persistent left trigeminal artery was noted in another. Hence, our observations are in conformity with earlier studies.

Conclusion

The morphological variations demonstrated by TOF-MRA in our study provide an important reference source for CW variations in the regional population. Our findings confirm the view that the configuration of the CW vary largely in our general population. The prevalence of complete configuration of the circle was16.6% and is slightly higher in females than males and younger (below 50 years) than older subjects. Complete anterior CW is more common with incidence of 77.3% of all the subjects. The most common anterior circle variant is type A (normal anterior configuration) with a prevalence of 66%. The most common posterior circle variant is type E (hypoplasia or absence of both Pcom As and isolation of the anterior and posterior parts of the circle at this level) with incidence of 32.6%. Overall, CW variants are slightly more common among the women in comparison to men. Incidence of associated anomalies, like aneurysm and AVM, is comparable to that described in literature.

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