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Original Article

Circle of Willis Variations Detected by Time of Flight Magnetic Resonance Imaging Angiography in Eastern Anatolia Region

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Abstract

Objective: The purpose of the study was to determine variations in the circle of Willis in the Eastern Anatolia Region with TOF magnetic resonance imaging angiography.

Methods: Two hundred fifty cases between the ages of 18 and 50, who applied to the department for cranial magnetic resonance angiography (MRA) examination and had no specific symptoms, were included in the study. Study data were obtained with 1.5 T and 3T MR (Magnetom Skyra; Siemens Healthcare, Erlangen, Germany) devices.

Results: Typical polygonal structure was seen in 80 cases (32%) and arteria communicans anterior (AComA) aplasia was seen in 4 cases (1.62%). The incidence of right and left anterior cerebral artery (ACA) A1 aplasia and hypoplasia were 11 (4.4%), 5 (2%), 14 (5.5%), and 6 (2.4%), respectively. ACA trifurcation was detected in 19 (7.6%), azygos ACA in 2 (0.8%), and bi-hemispheric ACA in 4 (1.6%). Right and left arteria communicans posterior (AComP) aplasia and hypoplasia were detected in 42 (16.8%), 32 (12.8%), 25 (10%), and 26 (10.4%), respectively. Right arteria cerebri posterior (ACP) fetal configuration was determined in 26 (10.4%), left in 15 (6%), and bilateral in 16 (6.4%). Basilar artery fenestration and persistent trigeminal artery were detected in 3 cases (1.2%). Right and left vertebral artery hypoplasia was determined in 20 (8%) and 14 (5.6%) cases, respectively.

Conclusion: The anatomical determination of the normal structure and variations of the Willis polygon with TOF MRA, which is a non-invasive imaging method that does not require radiation exposure and contrast material, revealed that the typical polygonal structure where all the arteries are located was detected at a rate of 32%. The most frequently detected variations were aplasia/hypoplasia, and they were seen most frequently in AComP (between 10% and 16.8%). The most frequently detected variation in anterior circulation was ACA trifurcation (7.6%), and it was similar to the literature.

Keywords: Anatomic variation, circle of Willis, magnetic resonance angiography, magnetic resonance imaging

INTRODUCTION

The circle of Willis is a ring of vessels that form a connection between anterior and posterior circulation. Both internal carotid arteries (ICAs) give off an ophthalmic artery and form anterior cerebral artery (ACA) and middle cerebral artery (MCA). The anterior communicating artery (ACom) connects bilateral ACAs. The posterior communicating artery (PCom) connects the MCA with the posterior cerebral arteries (PCAs). The basilar artery (BA) divides into 2 to form PCAs.[1]

The circle of Willis is the basic structure that ensures constant and regular blood flow to the brain in order to protect it from ischemia. The studies of the British anatomist Sir Thomas Willis in the 17th century forms the basis of the anatomical knowledge one has about the brain and vascular anatomy today.[2] Today, the studies of Yaşargil and Rhoton form the basis of the vascular anatomy of the modern central nervous system.[3,4] Although there are detailed studies of each artery forming the circle in the literature, studies that include the whole circle are relatively few. In addition, while there are few studies on the circle of Willis in the adult population in the Turkish society in the literature, no such study has been found for the Eastern Anatolia region.

Collateral circulation in circle of Willis is important in maintaining adequate cerebral blood flow in case of obstructive arterial diseases. There are 2 types of collateral vessels: extracranial and intracranial collateral vessels. Intracranial collateral vessels are formed by primary collaterals which connect the arterial segments of the circle of Willis and secondary collaterals such as leptomeningeal vessels that form after an insult when primary collaterals are not sufficient.

There are studies reporting higher frequency of incomplete circle of Willis in migraine patients in particular in migraine patients with aura.[5] Thus variations in the posterior circulation are found to be a contributing factor to stroke in migraine patients.[6]

The purpose of the study is to determine incidence of anatomical variants in Eastern Anatolia Region and compare it to the literature.

MATERIAL AND METHODS

Patient Group

The single-institution, prospective study was approved by the institutional ethics committee of Atatürk University (Ethics Committee number: B.30.2.ATA.0.01.00/277, date: May 30, 2019). Written informed consent forms were signed by all study participants.

In this study, it is aimed to prospectively investigate the presence and localization of circle of Willis variations in TOF magnetic resonance angiography (MRA) images obtained for various indications between 2019 and 2020. Two hundred fifty cases were included between the ages of 18 and 50 without specific symptoms in the study. Exclusion criteria as follows: patients with brain surgery or aneurysmal coil embolization, patients younger than 18, and images without adequate quality to assess vascular structures due to artifacts. Patients over 50 years old were excluded from the study due to concerns regarding age-related vascular changes and confounding comorbidities. Pathological cases that would make it difficult to evaluate vascular structures and variations were excluded. In each case, the normal anatomy of the circle of Willis and its variations were evaluated and noted separately.

Magnetic Resonance Imaging Protocol

The study was performed with 1.5 T and 3T MR (Magnetom Skyra; Siemens Healthcare, Erlangen, Germany) devices. There was not exposure to radiation and no contrast material was used. The images on workstations that provide multi-planar imaging and noted the variations for each case were evaluated.

Magnetic Resonance Imaging Evaluation

Images were evaluated by 1 radiologist with 10 year experience in neuroradiology. Axial, coronal, sagittal images and multi-planar reconstructions were all evaluated together. The variations that were evaluated in the study are as follows: AComA aplasia, right and left ACA A1 aplasia-hypoplasia, ACA trifurcation (Figure 1), azygos ACA (Figure 2), bi-hemispheric ACA, right and left AComP aplasia-hypoplasia (Figure 3), right, left, and bilateral ACP fetal configuration, persistent trigeminal artery (PTA) (Figure 4), fenestration in BA, hypoplasia in right and left vertebral artery. Absence of an artery is diagnosed as aplasia and a diameter smaller than 1 mm as hypoplasia.

Statistical Analysis

Analyses were performed using the IBM SPSS 20 (IBM SPSS Corp.; Armonk, NY, USA) statistical analysis program. Shapiro–Wilk W test and Kolmogorov–Smirnov test were used to check the normal distribution of continuous variables. In comparisons between 2 independent groups consisting of male and female subjects, the Independent Samples *t* test was used when the normal distribution condition was met, and the Mann–Whitney *U* test was used when it was not met. In 2 × 2 comparisons between categorical variables (>5), the Pearson chi-square test was used, the chi-square Yates test was used for expected values (3-5), and Fisher's exact test was used for expected values (<3). Statistical significance level was taken as $P < .05$.

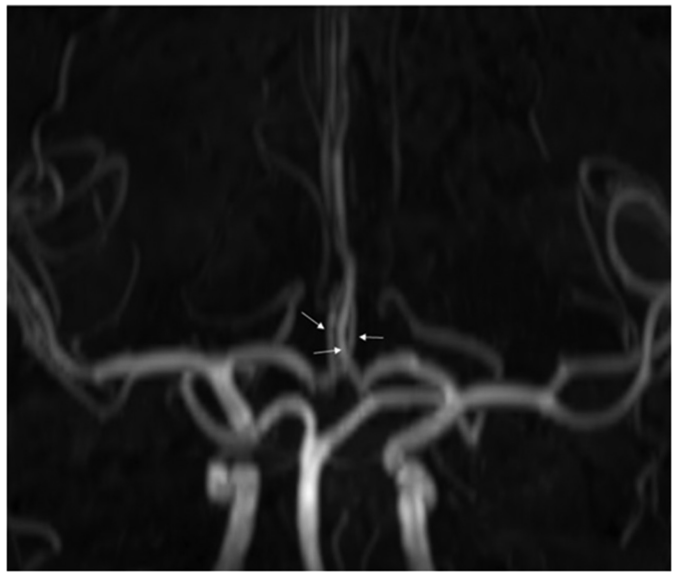

Figure 1. ACA trifurcation in A2 segment (thin arrows).

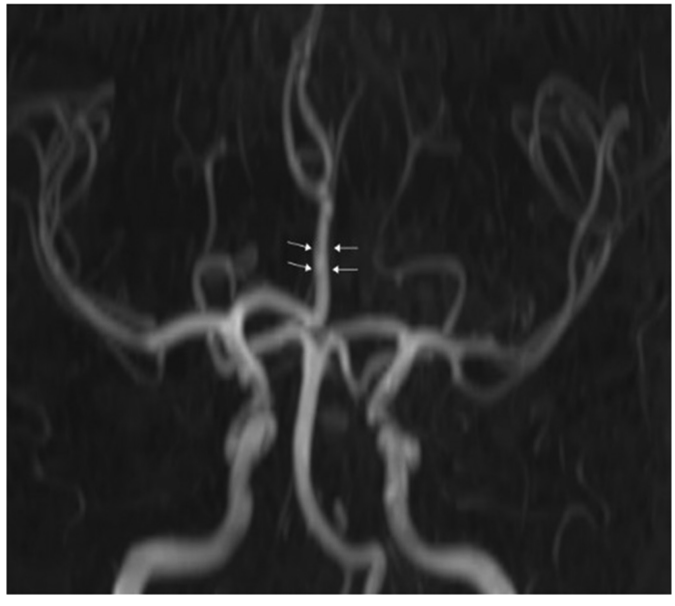

Figure 2. Azygos variation in ACA A2 segment (thin arrows).

MAIN POINTS

- Two hundred fifty patients without specific neurological symptoms were evaluated to determine circle of Willis variations in the Eastern Anatolia region.
- The typical polygonal structure where all the arteries are located was detected at a rate of 32%.
- Willis polygon variations were more frequent in the posterior part of the polygon, consistent with the literature.
- The most frequently detected variations were aplasia/hypoplasia, with the most frequently detected was arteria communicans posterior (between 10% and 16.8%).
- The most frequently detected variation in anterior circulation was arteria cerebri anterior trifurcation (7.6%), and it was similar to the literature.

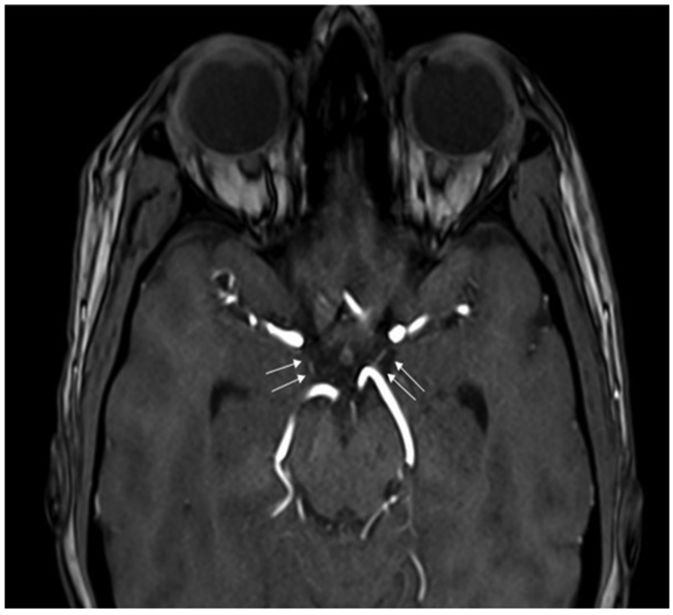

Figure 3. Bilateral hypoplasia of arteria communicans posterior.

RESULTS

Patient Demographics

Study group consisted of 250 patients, 95 were male (38%) and 155 were female (62%). The age range was 18-50 for both genders, and the mean age was 36 for males and 35.8 for females.

The typical (complete-normal) polygonal structure in which all arteries forming the circle of Willis were present was observed in a total of 80 cases (32%). The number and rates of variations in the study group are summarized in Table 1; the distribution of variations by gender is summarized in Table 2.

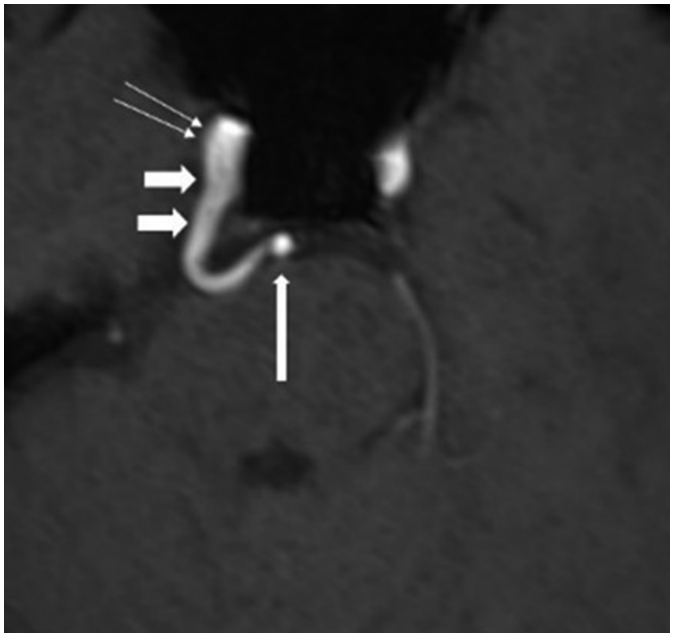

Figure 4. Persistent trigeminal artery between the right internal carotid artery (ICA) and the basilar (ICA - thin arrows, basilar artery - long arrow, and persistent trigeminal artery - short thick arrows).

Table 1. Number and Percentages of Variations in Circle of Willis

		Number	Percentage (%)
A Com A Ap	1	4	1.6
R ACA A1 Ap	1	11	4.4
L ACA A1 Ap	1	5	2.0
R ACA A1 Hp	1	14	5.6
L ACA A1 Hp	1	6	2.4
ACA Trifurcation	1	19	7.6
Azygos ACA	1	2	0.8
Bi-hemispheric ACA	1	4	1.6
R A Com P Ap	1	42	16.9
L A Com P Ap	1	32	12.9
R A Com P Hp	1	25	10.0
L A Com P Hp	1	26	10.4
Fetal RPCA	1	26	10.4
Fetal LPCA	1	15	6.0
Fetal BPCA	1	16	6.4
BA fenestration	1	3	1.2
R VA V4 Hp	1	20	8.0
L VA V4 Hp	1	14	5.6
PTA	1	3	1.2

A Com A Ap, Arteria Communicans Anterior Aplasia; ACA, Anterior Cerebral Artery; BA, basilar artery; BPCA, bilateral Posterior Cerebral Artery; Hp, hypoplasia; L A Com P Ap, left Arteria Communicans Posterior Aplasia; L A Com P Hp, left Arteria Communicans Posterior Hypoplasia; L ACA A1 Ap, left Anterior Cerebral Artery A1 Aplasia; L ACA A1 Hp, left Anterior Cerebral Artery A1 hypoplasia; LPCA, left Posterior Cerebral Artery; PTA, persistent trigeminal artery; R A Com P Ap, right Arteria Communicans Posterior Aplasia; R A Com P Hp, right Arteria Communicans Posterior Hypoplasia; R ACA A1 Ap, right Anterior Cerebral Artery A1 Aplasia; R ACA A1 Hp, right Anterior Cerebral Artery A1 Hypoplasia; RPCA, right Posterior Cerebral Artery; VA, vertebral artery.

AComA aplasia was detected in a total of 4 cases (1.62%). Right ACA A1 segment aplasia and left ACA A1 segment aplasia were detected in numbers and ratios of 11 (4.4%) and 5 (2%), respectively. Right ACA A1 segment hypoplasia and left ACA A1 segment hypoplasia were detected in 14 (5.5%) and 6 (2.4%) numbers and rates, respectively. There are 3 A2 segments in the ACA trifurcation, also called the persistent medial callosal artery. The number of cases in which ACA trifurcation was detected is 19 (7.6%). While the most common variation in the anterior circulation was ACA trifurcation (7.6%), the least common variation was azygos ACA variation. A single A2 is observed in azygos ACA variation. In general, the majority of the variations that were detected belonged to the posterior circulation. The most common variations that was detected were aplasia and hypoplasia. The localization in which aplasia and hypoplasia were detected most frequently is AComP. The variations detected in the posterior circulation and their numbers are as follows: Right AComP aplasia and left AComP aplasia were detected in the numbers and ratios of 42 (16.8%) and 32 (12.8%), respectively.

Variations of the fetal ACP configuration constitute the second most frequently detected variation group after aplasia and hypoplasia. These variations were determined according to the relationship between the AComP and ACP P1 segment diameters; cases where the AComP diameter is larger than the ACP P1 segment are called fetal configuration. In this study, the fetal configuration of the ACP wes grouped as right, left, and bilateral. In this group, the right fetal configuration was determined as 26 (10.4%), the left fetal configuration as 15 (6%), and the bilateral fetal configuration as 16 (6.4%). The term fenestration refers to the appearance of the vascular structure ending with the division of its lumen into 2 sections, each with its own endothelial layer, running parallel to each other and then reuniting. In this

Table 2. Distribution of Variations According to Genders

		Gender					
		M		F			
		Number	Percentage (%)	Number	Percentage (%)	Chi-Square	*P*
A Com A Ap	1	2	2.1	2	1.3		.64
R ACA A1 Ap	1	6	6.3	5	3.2	0.69	.41
L ACA A1 Ap	1	2	2.1	3	1.9		1
R ACA A1 Hp	1	7	7.4	7	4.5	0.88	.35
L ACA A1 Hp	1	2	2.1	4	2.6		1
ACA Trifurcation	1	7	7.4	12	7.8	0.02	.90
Azygos ACA	1	2	2.1	0	0.0		.15
Bi-hemispheric ACA	1	3	3.2	1	0.6		.16
R A Com P Ap	1	20	21.1	22	14.3	1.92	.17
L Com P Ap	1	11	11.6	21	13.6	0.22	.64
R Com P Hp	1	8	8.4	17	11.0	0.45	.50
L Com P Hp	1	8	8.4	18	11.7	0.67	.41
Fetal RPCA	1	10	10.5	16	10.4	0.001	.97
Fetal LPCA	1	5	5.3	10	6.5	0.16	.69
Fetal BPCA	1	5	5.3	11	7.1	0.35	.56
BA fenestration	1	0	0.0	3	1.9		.29
PTA	1	1	1.05	2	1.3		.29
R VA V4 Hp	1	7	7.4	13	8.4	0.092	.76
L VA V4 Hp	1	7	7.4	7	4.5	0.882	.35

A Com A Ap, Arteria Communicans Anterior Aplasia; ACA, Anterior Cerebral Artery; BA, basilar artery; BPCA, bilateral Posterior Cerebral Artery; Hp, hypoplasia; L A Com P Ap, left Arteria Communicans Posterior Aplasia; L A Com P Hp, left Arteria Communicans Posterior Hypoplasia; L ACA A1 Ap, left Anterior Cerebral Artery A1 Aplasia; L ACA A1 Hp, left Anterior Cerebral Artery A1 hypoplasia; LPCA, left Posterior Cerebral Artery; PTA, persistent trigeminal artery; R A Com P Ap, right Arteria Communicans Posterior Aplasia; R A Com P Hp, right Arteria Communicans Posterior Hypoplasia; R ACA A1 Ap, right Anterior Cerebral Artery A1 Aplasia; R ACA A1 Hp, right Anterior Cerebral Artery A1 Hypoplasia; RPCA, right Posterior Cerebral Artery; VA, vertebral artery.

study group, fenestration was detected in the BA in 3 cases (1.2%). The number and rates of cases in which the authors detected right and left vertebral artery V4 segment hypoplasia are 20 (8%) and 14 (5.6%), respectively.

Although PTA variation is rare in the population, it is the most common variation among persistent carotid-BA variations. Persistent trigeminal artery variation was detected in a total of 3 cases (1.2%) in this study group.

There is not any statistically significant difference between age and gender in terms of the frequency and localization of variations.

DISCUSSION

Various variations of the Willis polygon have been defined in the literature, and the names, numbers, criteria, and diversity of the variations included in the studies vary. This is the main reason for the significant difference in the rate of variation among studies. In addition, it is seen that there is no consensus on the definition of hypoplasia, and the cut-off value for hypoplasia is taken as 0.5 mm, 0.8 mm, or 1 mm in different studies.[3,7,8]

Variations of the circle of Willis are more frequently seen in the posterior part of the circle. The most common localization has been reported as AComP in a cadaver study by Karataş et al.[9] In another study by Karataş et al[9] examined variations of aplasia, hypoplasia, and fetal ACP in their 100-case study with CTA, and accepted the hypoplasia criterion as 1 mm, and found a variation rate of 72%, and the most common variation was AComP hypoplasia with a rate of 22%.[10] In this study, variations were more frequent in the posterior part of the circle, in line with the literature. The most frequently detected variations were AComP aplasia and hypoplasia. Right AComP aplasia was 16.8% and left AComP aplasia was 12.8%; right AComP hypoplasia was 10% and left AComP hypoplasia was 10.4%.

In a study conducted on 1205 cases with CTA, a total of 21 variations were examined, the hypoplasia limit was accepted as 1 mm, variation was detected in 95.4% of the cases, and the most frequently detected variation was reported as AComP hypoplasia, detected at a rate of 32%.[11] In cerebral aneurysm treatments and carotid ligation, accurate determination of the polygon structure and variations is very important in terms of determining adequate cerebral circulation. Variations of the Willis polygon are frequently seen, but they usually do not cause serious clinical consequences. However, it should not be forgotten that the presence of hypoplasia or aplasia of AComP in nternal carotid artery occlusions is an independent risk factor for cerebral infarction. Therefore, unilateral ligation of the ACI in such a case can cause very important clinical problems.

Leptomeningeal collaterals cannot form in fetal variant of circle of Willis since both MCA and PCA are connected to ICAs. Thus there is an increased risk for stroke in patients with fetal PCA variant with obstructive arterial disease.[12] In AComP aneurysms, in the presence of fetal ACP configuration; AComP should be protected. Variations may develop outside the normal polygonal structure. However, it is not known exactly why and when these variations develop. Padget defined 3 configurations according to AComP and ACP diameters.[13] The type called adult configuration represents the situation where the diameter of AComP is smaller than the P1 segment of ACP. Adult configuration was found to be 87% in a study performed on 100 cadavers by Karataş et al.[9] The adult configuration was detected at a rate of 72% in the study. In the second type called fetal configuration; the diameter of AComP is larger than the P1 segment of ACP. Therefore, the vascularization of the occipital lobe is largely provided by the internal carotid

artery. The frequency of this configuration in adults was reported in 9% by Karataş et al.[9] In this study group, frequency of fetal configuration was 0.4% for right fetal configuration, 6% for left fetal configuration, and 6.4% for bilateral fetal configuration. Transitional configuration, in which the diameter of AComP and P1 are equal, was found in 5.2%.

The term fenestration refers to the appearance of the vascular structure during its course, when its lumen divides into 2 sections, each with its own endothelial layer, and runs parallel to each other, and then reunites. Data on the incidence of BA fenestration vary in the literature. It has been found to be 0.28%-5.26% in autopsy series, 0.3%-0.6% in studies conducted with angiography, and 1.0%-2.7% in MRA series.[14] In this study group, BA fenestration was found to be present in 1.2% of patients, similar to MRA series. Persistent carotid-basilar anastomoses are rare variations. Among these, the most common is the PTA variation seen between the ICA cavernous segment and the BA, with a rate of 83%. Its incidence is between 0.1% and 0.6% in cerebral angiographies. It is mostly seen unilaterally. The PTA regresses after the development of AComP. It is important to know this variation, especially in cases of trans-sphenoidal surgery. In this study, PTA variation was detected in 3 cases (1.2%).

Variations in the anterior section of the polygon are less frequently detected than in the posterior section, but are important in terms of pathologies such as aneurysms that may accompany. ACA A1 segment aplasia is a rare variation and has been observed at rates ranging from 0.3% to 2% in anatomic studies and 0.7% to 2% in angiographic series.[15] In this study, right ACA A1 aplasia was detected at a rate of 4.4% and left ACA A1 aplasia was detected at a rate of 2%. While ACA A1 segment hypoplasia is seen between 1% and 10% in the literature,[16] right ACA A1 hypoplasia was detected at a rate of 5.5% and left ACA A1 hypoplasia was detected at a rate of 2.4% in this study. In another study conducted with CTA, A1 segment aplasia was reported at a rate of 6% and A1 segment hypoplasia at a rate of 1%. In the same study, it was emphasized that the rate of A1 aplasia was detected at a higher rate than in the literature and AComA aneurysm was observed in 16% of the cases.[11] In a study by Kapoor et al,[17] A1 segment aplasia was found to be 0.4% and hypoplasia was detected in 1.7%. Both A1 aplasia and hypoplasia was detected at a higher rate in this study. The difference between results among different studies may be related to genetic, environmental, or combination of these factors and these factors should be further investigated. Another variation related to the anterior circulation in the literature is ACA trifurcation, which was reported at a rate of 8%.[10] In this study, a similar rate of ACA trifurcation variation was detected (7.6%).

Variations are common, but most of them do not pose a serious problem in the clinic. Again, the recovery levels of patients in occlusive vascular diseases can be explained by variations in the Willis polygon. The fact that various branches of the polygon are too thin to function or are completely absent is very important in occlusive vascular diseases and cerebrovascular surgery. In patients undergoing surgical intervention, anatomical determination of the normal structure and variations of the Willis polygon with TOF MRA, which is a non-invasive imaging method that does not require radiation exposure or contrast material, will help reduce the significant neurological complications that may arise and the associated morbidity and mortality risk. However, MRA has disadvantages such as being sensitive to motion artifacts and application limitations in patients with devices such as pacemakers, neurostimulators, and infusion pumps. Again, it should be kept in mind that hypoplasia or aplasia diagnoses may not be sufficiently reliable due to technical difficulties in evaluating arteries with diameters smaller than 1 mm in TOF MRA examination.

In conclusion, TOF MRA can be used to evaluate cerebral vascular anatomy, especially for screening and pre-surgical evaluation of asymptomatic or normal individuals. In cerebrovascular interventions, knowing anatomical variations and demonstrating the anomaly in advance is important for safe surgical intervention. Although TOF MRA can be used to examine circle of Willis without radiation exposure and the need for contrast material; technical difficulties in imaging some vessels, MRA's sensitivity to motion artifacts, and some application limitations such as pacemakers should be considered as disadvantages of the method.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: Ethics committee approval was received for this study from the ethics committee of Atatürk University (Approval No: B.30.2.ATA.0.01.00/277; Date: 30.05.2019).

Informed Consent: Written informed consent was obtained from patients who agreed to take part in the study.

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REFERENCES

1. Rosner J, et al. Neuroanatomy, circle of Willis. *StatPearls*. 2025.
2. Grand W. The anatomy of the brain, by Thomas Willis. *Neurosurgery*. 1999;45(5):1234-6; disscusion 1236. [CrossRef]
3. Rhoton AL, Jr. The supratentorial arteries. *Neurosurgery*. 2002;51(4)(suppl):S53-S120.
4. Rengachary SS, Xavier A, Manjila S, et al. The legendary contributions of Thomas Willis (1621-1675): the arterial circle and beyond. *J Neurosurg*. 2008;109(4):765-775. [CrossRef]
5. Hamming AM, van Walderveen MAA, Mulder IA, et al. Circle of Willis variations in migraine patients with ischemic stroke. *Brain Behav*. 2019;9(3):e01223. [CrossRef]
6. van Seeters T, Hendrikse J, Biessels GJ, et al. Completeness of the circle of Willis and risk of ischemic stroke in patients without cerebrovascular disease. *Neuroradiology*. 2015;57(12):1247-1251. [CrossRef]
7. Krabbe-Hartkamp MJ, van der Grond J, de Leeuw FE, et al. Circle of Willis: morphologic variation on three-dimensional time-of-flight MR angiograms. *Radiology*. 1998;207(1):103-111. [CrossRef]
8. Riggs HE, Rupp C. Variation in form of circle of Willis. The relation of the variations to collateral circulation: anatomic analysis. *Arch Neurol*. 1963;8:8-14. [CrossRef]
9. Karatas A, Yilmaz H, Coban G, Koker M, Uz A. The anatomy of Circulus arteriosus cerebri (circle of Willis): A study in Turkish population. *Turk Neurosurg*. 2016;26(1):54-61. [CrossRef]
10. Karatas A, Coban G, Cinar C, Oran I, Uz A. Assessment of the circle of Willis with cranial tomography angiography. *Med Sci Monit*. 2015;21:2647-2652. [CrossRef]
11. Kahraman F, İntraserebral WPV. Multiple Anevrizmalarla Olan ilişkisi. *Relat Between Var Circle Willis Mult Intracerebral Aneurysms*. 2020.
12. van Raamt AF, Mali WPTM, van Laar PJ, van der Graaf Y. The fetal variant of the circle of Willis and its influence on the cerebral collateral circulation. *Cerebrovasc Dis*. 2006;22(4):217-224. [CrossRef]
13. DH P. Intracranial arterial aneurysms. In: DH P, ed. *The circle of Willis Its embryology and anatomy*; 1944:67-90.

14. Sogawa K, Kikuchi Y, O'uchi T, Tanaka M, Inoue T. Fenestrations of the basilar artery demonstrated on magnetic resonance angiograms: an analysis of 212 cases. *Interv Neuroradiol*. 2013;19(4):461-465. [CrossRef]
15. Şahin H, Pekçevik Y. Anatomical variations of the circle of Willis: evaluation with CT angiography. *Anatomy*. 2018;12(1):20-26. [CrossRef]
16. Mäurer J, Mäurer E, Perneczky A. Surgically verified variations in the A1 segment of the anterior cerebral artery. Report of two cases. *J Neurosurg*. 1991;75(6):950-953. [CrossRef]
17. Kapoor K, Singh B, Dewan LIJ. Variations in the configuration of the circle of Willis. *Anat Sci Int*. 2008;83(2):96-106. [CrossRef]