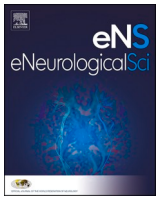
eNeurologicalSci 35 (2024) 100501

Contents lists available at ScienceDirect

eNeurologicalSci

journal homepage: www.elsevier.com/locate/ensci



Effect of moyamoya disease on the basilar artery and adjacent arteries on CTA

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ARTICLE INFO

Keywords:
Moyamoya disease
Basilar artery
Computed tomography angiography
Anatomy

ABSTRACT

Background: Computed tomographic angiography (CTA) is rarely used to explore the effect of moyamoya disease (MMD) on the basilar artery (BA) and its adjacent arteries.
Methods: Participants were divided into a control group and an MMD group. The relevant parameters were measured. Statistical analyses included the *t*-test, chi-squared test, and linear regression analysis.
Results: In the control group of 100 healthy people, the average age was 54.51 ± 13.40 years, and the ratio of males to females was 0.89:1. In the MMD group of 100 patients, the average age was 53.95 ± 11.31 years, and the ratio of males to females was 1.13:1. In the MMD group, the CTA score of the anterior circulation of the bilateral hemispheres was 7.57 ± 2.36. According to the statistical analyses, (1) in the control group, the BA apex tended to lean to the right in healthy participants; (2) in the MMD group, the BA was closer to the midline, and the angle between the BA and anterior inferior cerebellar artery was reduced, indicating that the BA was relatively elevated; (3) in the MMD group, the diameters of the BA, PCA and vertebral artery were larger than those in the control group; and (4) MMD patients with posterior cerebral atery (PCA) involvement had higher CTA scores of the anterior circulation.
Conclusions: MMD can cause the BA to move toward the midline and upward and enlarge major vessels of the posterior circulation. The PCA tends to be involved in MMD patients with higher CTA scores in the anterior circulation.

1. Introduction

Moyamoya disease (MMD) is characterized by progressive stenosis or occlusion of the internal carotid artery (ICA) termination, after which the middle cerebral artery (MCA), anterior cerebral artery (ACA), and even posterior cerebral artery (PCA) are subsequently stenosed or occluded (1).

In MMD, the posterior circulation is often preserved as an important collateral route to compensate for the anterior circulation (2). Due to hemodynamic stress, the posterior circulation may experience morphological remodeling of vessel diameters and degrees (3). The posterior circulation mainly focuses on the basilar artery (BA) and its adjacent arteries, including the PCA, the superior cerebellar artery (SCA), the anterior inferior cerebellar artery (AICA) and the vertebral artery (VA) (4,5).

Clarifying the remodeling of the posterior circulation is important because this knowledge can help neurosurgeons and neurointerventionists facilitate operations such as extracranial-intracranial revascularization and endovascular treatment for intracranial ischemic or hemorrhagic vascular diseases (6–9). Morphological remodeling of the BA and its adjacent arteries in MMD patients has rarely been studied using computed tomographic angiography (CTA) (1,10,11). Therefore, we performed a study using head CTA. In addition, this study also provided relevant data from Han Chinese people.

2. Materials and methods

A CTA study was performed on Chinese people of Han nationality who were healthy during routine physical examinations and patients with MMD between Jan 2018 and August 2021. The ethics committee of our hospital approved this study. All methods were performed in accordance with the relevant guidelines and regulations.

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https://doi.org/10.1016/j.ensci.2024.100501
Received 6 March 2024; Received in revised form 16 April 2024; Accepted 3 May 2024
Available online 5 May 2024

2.1. Inclusion criteria and grouping

2.1.1. Inclusion and exclusion criteria

(a) Contrast agent filling showing clear intracranial arteries, with no occupying or vascular lesions that could affect the measurement and recording of the parameters. (b) Bilateral MMD diagnosed by CTA showing bilateral steno-occlusive changes in the vessels of the anterior circulation (ICA, MCA, and ACA) (Fig. 1) (12,13). (c) Participants with a smoking history were not excluded. (d) Participants with atherosclerosis or coexisting cardiovascular disease were excluded.

2.1.2. Grouping

Healthy people were enrolled in the control group; patients with MMD were enrolled in the MMD group.

2.2. Software and tools used for postprocessing

The raw data were postprocessed using a GE Workstation (version 4.7) (GE Healthcare; Cytiva). The data were primarily reconstructed using the volume rendering tool. Structures that interfered with the measurement were removed using the cutting tool. The vessel diameter was obtained using the measuring distance tool. The curved length of a vessel was measured using the two-click AVA tool. The angle between the vessels was measured by the degree tool. All of the parameters were measured 3 times by Han Su and Jinlu Yu, and the average value was used.

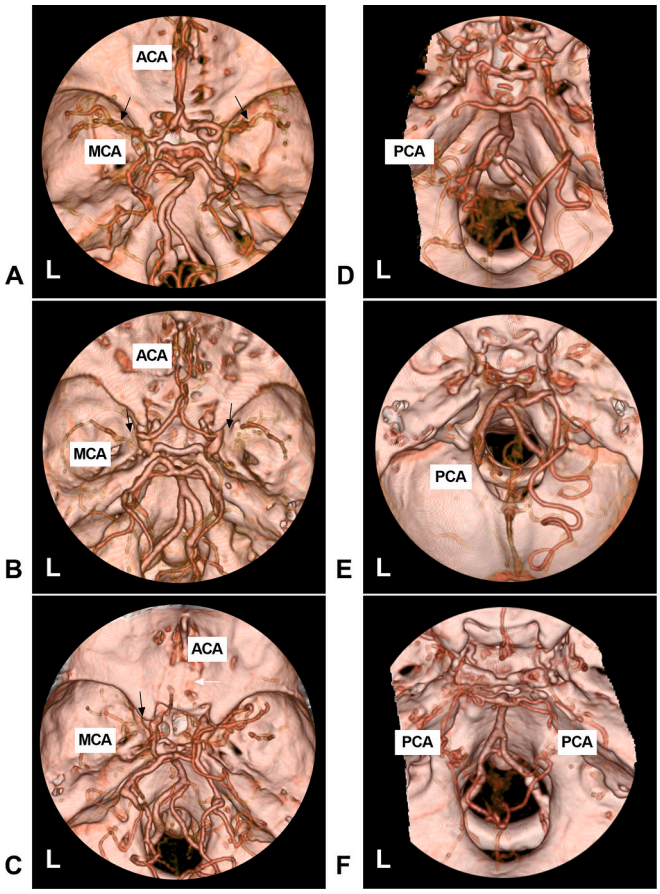

Fig. 1. MMD presentation on CTA.
A: CTA showing stenosis of the bilateral MCA trunk (black arrows), and the ACA was normal. B: CTA image showing a discontinuity of the bilateral MCA trunk (black arrows) and a normal ACA. C: CTA image showing a discontinuity of the left MCA trunk (black arrow) and an invisible ACA (white arrow). D: CTA image showing a discontinuity of the left PCA and its distal region (black arrow). E: CTA image showing an invisible left PCA and its distal segment. F: CTA image showing bilateral PCAs with discontinuity of the distal PCAs.
Abbreviations: ACA: anterior cerebral artery, CTA: computed tomographic angiography, ICA: internal carotid artery, L: left, MCA: middle cerebral artery, MMD: moyamoya disease, PCA: posterior cerebral artery.

2.3. Recorded and measured parameters

The MMD scores of the anterior circulation were recorded based on the CTA scoring system of Houkin et al. (Fig. 1) (12,13). The scores for the ICA were as follows: Point 0: normal or equivocal stenotic intracranial ICA; Point 1: apparent stenotic intracranial distal ICA; Point 2: severe decrease or discontinuity of the intracranial distal ICA; and Point 3: both intracranial distal ICAs were difficult to identify. The scores for the MCA are as follows: Point 0: normal or equivocal stenotic M1 portion; Point 1: moderate stenotic change in the M1 portion; Point 2: severe signal decrease or loss of the M1 portion and its distal branches; and Point 3: the M1 portion and its distal branches are difficult to identify. The scores for the ACA were as follows: Point 0: normal or equivocal stenotic distal ACA; Point 1: A2 and its distal branches decrease; and Point 2: distal ACAs are difficult to identify. PCA involvement in MMD patients was divided into normal (point 0), discontinuous (point 1), and invisible P2s and their distal segments (point 2).

The vessel diameters included the diameters of the PCA at its origin, the SCA at its origin, the BA at its origin and termination, the AICA at its origin, and the VA at its termination. The lengths included the length of the BA from the VA to the AICA and the whole BA length. The angles included the angles between the BA and SCA, between the BA and PCA, between the BA and AICA, between the VA and BA, between the bilateral PCAs, and between the bilateral VAs (Fig. 2).

2.4. Variation and development

Variation and development of the vessels were recorded, including absence, duplication, and hypoplastic and hyperplastic changes. In addition, fenestration in the vessel was also recorded. These are illustrated in Figs. 3–4.

2.5. Statistical analysis

Statistical assessments were performed using GraphPad Prism (10 LLC, San Diego, CA, USA). Continuous variables are expressed as the means ± standard deviations, and differences were assessed using the *t*-test. The chi-squared test or Fisher's exact-test was used to analyze the count data. The relationships between independent variables and dependent variables were analyzed using linear regression. $P < 0.05$ was considered to indicate statistical significance.

3. Results

3.1. General information

In the control group of 100 healthy people, the average age of the patients was 54.51 ± 13.40 years (range, 10–84 years), the ratio of males to females was 0.89:1 (47/53), and the percentage of smokers was 34% (34/100). In the MMD group of 100 patients, the average age was 53.95 ± 11.31 years (range, 11–74 years), the ratio of males to females was 1.13:1 (53/47), and the percentage of smokers was 35% (35/100) (Table 1).

3.2. Clinical presentation, MMD CTA scores, and PCA involvement

In the MMD group, 30 (30%, 30/100) patients presented with intraventricular hemorrhage, 22 (22%, 22/100) with intracerebral hematoma, 14 (14%, 14/100) with subarachnoid hemorrhage, and 34 (34%, 34/100) with cerebral infarction. The CTA score of the anterior

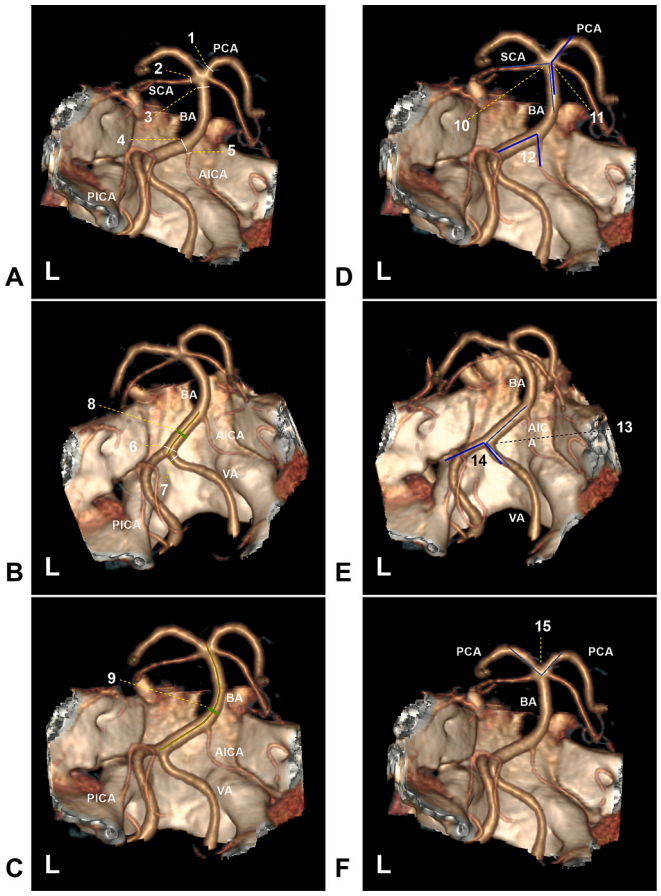

Fig. 2. Parameter measurements on CTA.
A: No. 1 is the diameter of the PCA at the origin, 2 is the diameter of the SCA at the origin, 3 is the diameter of the BA termination, 4 is the diameter of the BA at the AICA origin, and 5 is the diameter of the AICA at the origin. B: No. 6 is the diameter of the BA at the origin, 7 is the diameter at the VA termination, and 8 is the length of the BA from the VA to the AICA. C: No. 9 is the whole BA length. D: No. 10 is the angle between the BA and SCA, 11 is the angle between the BA and PCA, and 12 is the angle between the BA and AICA. E: No. 13 is the angle between the VA and BA, and 14 is the angle between the bilateral VAs. F: No. 15 is the angle between bilateral PCAs.
Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, CTA: computed tomographic angiography, L: left, PCA: posterior cerebral artery, PICA: posterior inferior cerebellar artery, R: right, SCA: superior cerebellar artery, VA: vertebral artery.

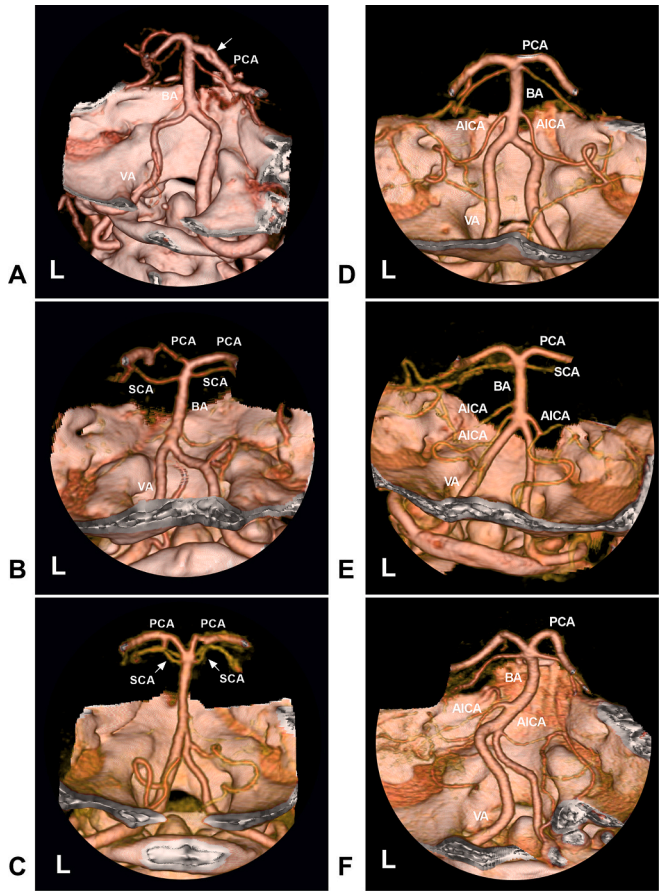

Fig. 3. Variation and development of the PCA, SCA and AICA on CTA.
A: CTA image showing a fenestration (arrow) on the right P1 segment. B: CTA showing a left SCA from the PCA. C: CTA image showing bilateral duplicated SCAs (arrows). D: CTA showing the AICA as a single trunk on both sides. E: CTA image showing a duplicated left AICA. F: CTA showing a right AICA originating from the VA termination site.
Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, CTA: computed tomography angiography, L: left, PCA: posterior cerebral artery, SCA: superior cerebellar artery, VA: vertebral artery.

circulation of the bilateral hemispheres in 100 MMD patients was 7.57 ± 2.36 (Table 2). PCA involvement was observed in 15 (15%, 15/100) patients (5 with ipsilateral P2 stenoses, 8 with ipsilateral P2 occlusions and 2 with bilateral P2 stenoses) (Table 3).

3.3. Measured parameters

3.3.1. PCA, SCA, AICA and VA diameters

In the control group, all 200 PCAs were measured; 183 (91.5%, 183/200) SCAs were measured, excluding 10 (5%, 10/200) duplicate SCAs and 7 (3.5%, 7/200) SCAs originating from the PCA; 164 (82%, 164/200) AICAs were measured, excluding 24 (12%, 24/200) invisible AICAs, 7 (3.5%, 7/200) duplicate AICAs and 5 (2.5%, 5/200) AICAs originating from the VA; and 198 (99%, 198/200) VAs were measured, excluding 2 (1%, 2/200) VAs with fenestration at their terminations.

In the MMD group, 199 (99.5%, 199/200) PCAs were measured, excluding 1 (0.5%, 1/200) invisible PCA; 1 (0.5%, 1/200) P1 fenestration was identified but did not affect the measurements. A total of 179 (89.5%, 179/200) SCAs were measured, excluding 12 (6%, 12/200) duplicate SCAs, 8 (4%, 8/200) SCAs originating from the PCA and 1 (0.5%, 1/200) invisible SCA; 158 (79%, 158/200) AICAs were measured, excluding 34 (17%, 34/200) invisible AICAs, 5 (2.5%, 5/200) duplicate AICAs, and 3 (1.5%, 3/200) AICAs originating from the VA; and 199 (99.5%, 199/200) VAs were measured, excluding 1 (0.5%, 1/200) VA that terminated at the posterior inferior cerebellar artery.

3.3.2. BA diameter and length

The BA diameters at the origin and termination and BA lengths were measured in both groups. Excluding duplicate or invisible AICAs or AICAs originating from the VA (mentioned in the previous sections) and BA fenestrations (6 (6%, 6/100) in the control group and 3 (3%, 3/100) in the MMD group), 160 (80%, 160/200) BA diameters at the AICA origin were measured in the control group, and 155 (77.5%, 155/200) in the MMD group; 164 (82%, 164/200) BA lengths from the origin to the AICA were measured in the control group, and 158 (79%, 158/200) were measured in the MMD group.

3.3.3. Angles between vessels

Among the angles between the BA and SCA, 183 (91.5%, 183/200) were measured in the control group, and 179 (89.5%, 179/200) were measured in the MMD group. A total of 100 angles between the BA and PCA (100%, 100/200) were measured in the control group, and 199

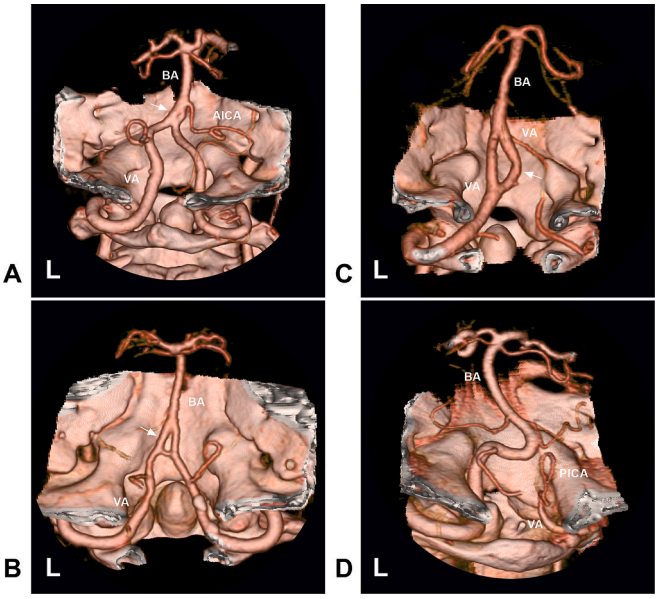

Fig. 4. Variation and development of the BA and VA on CTA.
A: CTA image showing a small fenestration below the AICA (arrow). B: CTA image showing a large fenestration, presenting as a triangular-shaped region (arrow). C: CTA showing a right hypoplastic VA and a left hyperplastic VA with a large fenestration (arrow) at the VA termination. D: CTA showing a right VA terminating at the PICA.
Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, CTA: computed tomographic angiography, L: left, PICA: posterior inferior cerebellar artery, VA: vertebral artery.

Table 1
General information.

	Control group	MMD group	*P* value
Age (years)	54.51 ± 13.40 (10–84)	53.95 ± 11.31 (11–74)	0.7499
Male/female	47/53	53/47	0.4796
Smokers (yes/no)	34/66	35/65	>0.9999

Abbreviations: MMD: moyamoya disease. In the table, age was compared with the unpaired t-test. Other parameters were compared with Fisher's exact-test.

Table 2
CTA scores of the anterior circulation in MMD patients.

Side	Score	Range	P value
Left (100 hemispheres)	3.87 ± 1.40	2–8	0.2003
Right (100 hemispheres)	3.70 ± 1.31	1–7	
Total (bilateral hemispheres in 100 patients)	7.57 ± 2.36	4–14	–

Abbreviations: CTA: computed tomography angiography, MMD: moyamoya disease. The data were compared with paired *t*-tests.

Table 3
CTA scores of the anterior circulation in MMD patients with/without PCA involvement.

Group	Score	Range	P value
15 patients with PCA involvement	9.33 ± 2.13	6–14	0.0014
85 patients without PCA involvement	7.26 ± 2.27	4–13	

Abbreviations: CTA: computed tomography angiography, MMD: moyamoya disease, PCA: posterior cerebral artery. In the table, the unpaired t-test was used for comparisons between groups.

(99.5%, 199/200) were measured in the MMD group. A total of 164 (82%, 164/200) angles between the BA and AICA were measured in the control group, and 158 (79%, 158/200) were measured in the MMD group. Regarding the angle between the BA and VA, 198 (99%, 198/200) joints were measured in the control group, and 199 (99.5%, 199/200) were measured in the MMD group. All angles between the bilateral PCAs were measured in the control group, and 99 (99%, 99/100) were measured in the MMD group. For the angle between the bilateral VAs, 98 (98%, 98/100) were measured in the control group, and 99 (99%, 99/100) were measured in the MMD group.

In section "3.3 Measured parameters", more results are shown in Tables 4–5.

3.4. Statistical results

3.4.1. Age, sex and smoking status

The unpaired *t*-test and Fisher's exact-test showed no significant difference in age, sex or smoking history between the two groups, indicating that these baseline data were similar (Table 1).

3.4.2. Data of the control group

The paired *t*-test showed that the BA at the termination site was thicker than the BA at the origin site ($P < 0.05$). The unpaired *t*-test showed that the left VA at termination was thicker than the right ($P < 0.05$). The paired t-test showed that the left angles between the BA and SCA and between the BA and PCA were larger than the right angles ($P < 0.05$). More results are shown in Table 4.

3.4.3. Data from the MMD group

The paired *t*-test showed that the difference in the MMD CTA scores between the left and right cerebral hemispheres was not significant ($P > 0.05$), indicating that MMD had the same effect on the bilateral cerebral hemispheres (Table 2). The unpaired t-test showed that the BA at the termination site was thicker than the BA at the origin site ($P < 0.05$). The unpaired t-test showed that MMD patients with PCA involvement had greater CTA scores for the anterior circulation ($P < 0.05$) (Table 3). More results are shown in Table 4.

Linear regression was used to analyze the relationships between the CTA scores of the anterior circulation of bilateral hemispheres in MMD patients and the diameters of the PCA at its origin, the BA at its origin, the AICA at its origin and termination, the VA at its termination, and the angle between the BA and AICA. The results showed that the MMD CTA score did not affect these parameters ($P > 0.05$) (Table 5).

3.4.4. Differences between groups

The unpaired *t*-test showed that the diameters of the BA, PCA and VA were greater in MMD patients ($P < 0.05$), indicating that MMD enlarged the major vessels of the posterior circulation. The unpaired t-test showed that the angle between the BA and AICA was reduced in MMD patients ($P < 0.05$), indicating that the BA moved upward overall, perhaps because the AICA was relatively fixed. More results are shown in Table 6.

4. Discussion

Currently, digital subtracted angiography (DSA) remains the gold standard for studying MMD, but its role has been partially eliminated by magnetic resonance angiography (MRA) and computed tomography angiography (CTA) because of their minimal invasiveness and convenience (14–16). A study by Sugino et al. confirmed that CTA is a reliable technique for diagnosing MMD (13). CTA can be performed to evaluate MMD based on the scoring system of Houkin et al. (12,13). The scoring system correlated well with the grading system of Suzuki et al. (12,13,17). Therefore, our CTA-based study was reasonable for studying MMD.

In the early stages, MMD predominantly affects the ICAs bilaterally, often sparing the posterior circulation (18). Subsequently, steno-occlusive changes in MMD patients progress from the anterior arteries to the posterior communicating artery (PcomA) and PCA because the

Table 4
Data of the control and MMD groups.

	Control group				MMD group			
Parameter	Sides	Range (mm)	Mean (mm)	P value	Sides	Range (mm)	Mean (mm)	P value
PCA diameter at the origin*	L (100)	0.5–3.9	1.95 ± 0.54	0.7481	L (99)	0.5–4.7	2.37 ± 0.74	0.6011
	R (100)	0.4–4.0	1.93 ± 0.65		R (100)	0.3–4.0	2.31 ± 0.76	
SCA diameter at the origin	L (93)	0.2–2.0	0.78 ± 0.43	0.1475	L (91)	0.3–1.9	0.82 ± 0.44	0.4328
	R (90)	0.3–2.0	0.88 ± 0.48		R (88)	0.2–2.2	0.88 ± 0.46	
BA diameter*	Origin (100)	2.0–4.6	3.00 ± 0.52	<0.0001	Origin (100)	2.1–5.7	3.31 ± 0.63	<0.0001
	Termination (100)	2.4–6.8	3.92 ± 0.74		Termination (100)	2.8–5.9	4.20 ± 0.72	
AICA diameter at the origin	L (79)	0.3–1.6	0.69 ± 0.28	0.4607	L (82)	0.2–1.9	0.67 ± 0.32	0.2151
	R (85)	0.3–1.5	0.72 ± 0.26		R (76)	0.3–1.7	0.74 ± 0.33	
BA diameter at the AICA origin	L (78)	2.2–6.5	3.66 ± 0.66	0.7287	L (80)	2.5–5.9	3.83 ± 0.69	0.8049
	R (82)	2.1–6.5	3.63 ± 0.69		R (75)	2.5–5.4	3.80 ± 0.63	
VA diameter at the termination	L (99)	0.5–5.8	2.69 ± 0.86	0.0016	L (100)	0.7–6.4	2.95 ± 0.80	0.0905
	R (99)	0.5–4.4	2.32 ± 0.75		R (99)	0.8–5.1	2.76 ± 0.84	
Length from the BA origin to the AICA origin	L (79)	1.6–22.2	8.54 ± 4.15	0.5675	L (82)	0.9–32.1	7.56 ± 4.56	0.6166
	R (85)	1.6–22.2	8.90 ± 3.99		R (76)	1.3–18.6	8.03 ± 3.09	
Angle between the BA and PCA*	L (100)	78.2–180	131.4 ± 18.08	0.0144	L (99)	82.3–178.8	129.5 ± 20.73	0.0894
	R (100)	75.6–176.1	124.3 ± 19.96		R (100)	54.3–171.2	124.6 ± 19.99	
Angle between the BA and SCA	L (93)	34.4–132.8	70.15 ± 16.96	0.0159	L (91)	26.2–121.3	69.82 ± 18.62	0.6053
	R (90)	30.7–96.8	64.43 ± 14.71		R (88)	9.5–109.7	68.36 ± 19.25	
Angle between the BA and AICA	L (79)	14.0–108.0	48.50 ± 16.75	0.4240	L (82)	13.2–94.0	42.28 ± 18.14	0.6758
	R (85)	13.3–91.8	50.64 ± 17.46		R (76)	10.4–80.7	43.79 ± 14.67	
Angle between the BA and VA	L (99)	101.1–180.0	150.9 ± 14.56	0.3052	L (100)	109.6–179.8	153.0 ± 14.66	0.7779
	R (99)	80.3–180.0	148.6 ± 16.64		R (99)	119.0–179.3	152.4 ± 14.65	

Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, L: left, MMD: moyamoya disease, PCA: posterior cerebral artery, R: right, SCA: superior cerebellar artery, VA: vertebral artery. In the table, parameters with asterisks were compared with paired t-tests; the other parameters were compared with unpaired t-tests.

Table 5
Linear regression between the CTA score and vessel diameter/angle.

Parameter X	Parameter Y	Equation	P value
PCA diameter at the origin	CTA score	Y = 0.01804*X + 2.200	0.5342
BA diameter at the origin	CTA score	Y = 0.02188*X + 3.143	0.4168
BA diameter at the AICA origin	CTA score	Y = 0.04329*X + 3.416	0.1321
BA diameter at the termination	CTA score	Y = 0.04367*X + 3.872	0.1544
Left VA diameter at the termination	CTA score	Y = 0.03037*X + 2.723	0.3750
Right VA diameter at the termination	CTA score	Y = 0.01298*X + 2.657	0.7180
Angle between the BA and AICA	CTA score	Y = 0.07146*X + 34.21	0.8959

Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, CTA: computed tomography angiography, PCA: posterior cerebral artery, VA: vertebral artery.

PcomA and PCA are involved in the caudal division of the primitive ICA (19). It is obvious that steno-occlusive changes in the cerebral arteries in MMD patients occur only in the arteries originating from the neural crest, such as the primitive ICA (20). In addition, mutations in the p.R4810K and DIAPH1 genes may affect PCA involvement in MMD (21,22).

Our study revealed that MMD patients with PCA involvement had greater CTA scores of the anterior circulation, supporting the above viewpoint that, with MMD progression, steno-occlusive changes in MMD will involve the PCA. In our study, 15% of MMD patients had PCA involvement, similar to the 15–30% of MMD patients reported to have PCA involvement during MMD progression in a previous study (5). PCA involvement in MMD is associated with increased rates of ischemic perioperative complications and worsened functional outcomes, likely due to reduced collateral flow (23).

Ultimately, MMD will result in stenosis and occlusion of the anterior circulation and PCA while sparing the posterior circulation of the vertebrobasilar system (24).

The core of the posterior circulation is the BA and its adjacent arteries. Based on the theory of embryological development, in MMD, the BA and its adjacent arteries are preserved and do not experience stenosis or occlusion (19). The posterior circulation serves as an important source of collateral circulation, and patients progressively experience remodeling due to hemodynamic pressure (3,7,25,26). These arteries may become dilated or displaced. Our study confirmed these changes and revealed that the BA moved toward the midline and upward and that the major vessels of the posterior circulation were enlarged.

In healthy people, the BA apex is not located at the midline and leans to the right because the left angles between the BA and SCA and between the BA and PCA are larger than those on the right. However, the angles in MMD patients are modified by hemodynamic remodeling of the major vessels, causing the BA apex to sit in the midline. In addition, in our study, the angle between the BA and AICA decreased in MMD patients, but the BA length did not change. A reasonable explanation is that the BA was pushed upward as a whole in MMD patients by hemodynamic pressure. Because the distal AICA is relatively fixed, as the BA moves upward, the distance between the BA and AICA decreases.

In addition, in our study, we found that although PCA stenosis or occlusion tended to be present in severe MMD patients, interestingly, MMD severity had no direct correlation with the degree of major vessel thickening, indicating that in the early stages of MMD, these vessels

Table 6
Comparison of the data between the groups.

Parameter	Groups	Range (mm)	Mean (mm)	P value
PCA diameter at the origin	Control (200)	0.4–4.0	1.94 ± 0.60	<0.0001
	MMD (199)	0.3–4.7	2.34 ± 0.75	
SCA diameter at the origin	Control (183)	0.2–2.0	0.83 ± 0.46	0.6394
	MMD (179)	0.2–2.2	0.85 ± 0.45	
BA diameter at the origin	Control (100)	2.0–4.6	3.00 ± 0.52	0.0002
	MMD (100)	2.1–5.7	3.31 ± 0.63	
BA diameter at the termination	Control (100)	2.4–6.8	3.92 ± 0.74	0.0074
	MMD (100)	2.8–5.9	4.20 ± 0.72	
AICA diameter at the origin	Control (164)	0.3–1.6	0.71 ± 0.27	0.8567
	MMD (158)	0.2–1.9	0.70 ± 0.32	
BA diameter at the AICA origin	Control (160)	2.1–6.5	3.65 ± 0.68	0.0271
	MMD (155)	2.5–5.9	3.81 ± 0.66	
Left VA diameter at the termination	Control (99)	0.5–5.8	2.69 ± 0.86	0.0245
	MMD (100)	0.7–6.4	2.95 ± 0.82	
Right VA diameter at the termination	Control (99)	0.5–4.4	2.32 ± 0.75	0.0002
	MMD (99)	0.8–5.1	2.76 ± 0.84	
BA length	Control (100)	2.0–5.9	31.3 ± 0.56	0.3368
	MMD (100)	2.1–5.6	30.6 ± 0.52	
Length from the BA origin to AICA	Control (164)	1.6–22.2	8.73 ± 4.06	0.0525
	MMD (158)	1.3–32.1	7.86 ± 3.87	
Angle between the BA and PCA	Control (200)	75.6–180.0	127.8 ± 19.3	0.6972
	MMD (199)	54.3–178.8	127.1 ± 20.5	
Angle between the BA and SCA	Control (183)	30.7–132.8	67.3 ± 16.1	0.3406
	MMD (179)	9.5–121.3	69.1 ± 18.9	
Angle between the BA and AICA	Control (164)	13.3–108.0	49.61 ± 17.11	0.0007
	MMD (158)	10.4–94.0	43.21 ± 16.52	
Angle between the BA and VA	Control (198)	80.3–180.0	149.8 ± 15.64	0.0530
	MMD (199)	109.6–179.8	152.7 ± 14.62	
Angle between the bilateral PCAs	Control (100)	44.7–168.5	100.9 ± 24.72	0.2777
	MMD (99)	16.2–174.8	105.0 ± 28.04	
Angle between the bilateral VAs	Control (98)	15.7–116.1	56.48 ± 18.94	0.0657
	MMD (99)	13.6–98.7	51.27 ± 20.50	
Diameter of PcomA at origin	Control (60)	0.3–2.5	1.60 ± 0.71	0.1969
	MMD (65)	0.5–3.0	1.77 ± 0.74	

Abbreviations: AICA: anterior inferior cerebellar artery, BA: basilar artery, MMD: moyamoya disease, PCA: posterior cerebral artery, PcomA: posterior communicating artery, SCA: superior cerebellar artery, VA: vertebral artery. In the table, the unpaired t-test was used.

undergo no further thickening or dilatation. Due to VA thickening, the difference between the left and right VA diameters disappeared. Interestingly, the diameters of smaller vessels, such as the SCA and AICA, were not affected, which indicated that hemodynamic pressure in MMD patients has a lesser effect on these vessels (Table 5).

In our study, the measured parameters were compared with those of other studies, such as Saeki et al. (27), Zeal et al. (28), Hardy et al. (29), Pai et al. (30) and Shrontz et al. (31). Due to racial differences and the imparity of measurement methods, there are some differences when comparing parameters obtained in different studies. Nevertheless, the parameters in the above studies were inconsistent. Therefore, our study is important because it provides data regarding Han Chinese people, a relatively underreported population.

In addition to morphological studies, cerebrovascular hemodynamic studies on MMD, such as cerebrovascular reserve capability, glymphatic system activity and the waste clearance system, are important (32,33). Hemodynamics studies of the BA and its adjacent arteries are warranted.

5. Conclusion

In summary, this CTA study provided normal anatomical data of the vessels of healthy people and MMD patients. In addition, this study revealed that in MMD patients, the BA and its major arteries are enlarged, while the minor arteries are not. Furthermore, the angles between the vessels are modified, and the BA and its major arteries are pushed upward as a whole.

6. Limitations

As a cross-sectional study, this study can only suggest an association between MMD and the parameters of the BA and its adjacent arteries and cannot fully confirm that the changes in these parameters are a result of MMD. Longitudinal analysis is the best choice for studying the effect of MMD on the BA and its adjacent arteries. However, it is difficult to follow up on such a longitudinal study. Despite these limitations, our study may reflect the tendency of MMD to affect the BA and its adjacent arteries.

CRediT authorship contribution statement

Han Su: Writing – review & editing, Writing – original draft, Data curation. **Jinlu Yu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] K. Hou, G. Li, Y. Guo, B. Xu, K. Xu, J. Yu, Angiographic study of the transdural collaterals at the anterior cranial fossa in patients with Moyamoya disease, Int. J. Med. Sci. 17 (13) (2020) 1974–1983.
[2] M. Zhao, D. Zhang, S. Wang, Y. Zhang, R. Wang, X. Deng, et al., Posterior circulation involvement in pediatric and adult patients with moyamoya disease: a single center experience in 574 patients, Acta Neurol. Belg. 118 (2) (2018) 227–233.
[3] K. Hou, G. Li, T. Luan, K. Xu, J. Yu, The prospects and pitfalls in the endovascular treatment of moyamoya disease-associated intracranial aneurysms, Neurosurg. Rev. 44 (1) (2021) 261–271.
[4] A.L. Rhoton Jr., The cerebellar arteries, Neurosurgery 47 (3 Suppl) (2000) S29–S68.
[5] J.Y. Lee, S.K. Kim, J.E. Cheon, J.W. Choi, J.H. Phi, I.O. Kim, et al., Posterior cerebral artery involvement in moyamoya disease: initial infarction and angle between PCA and basilar artery, Childs Nerv. Syst. 29 (12) (2013) 2263–2269.
[6] J. Yu, L. Shi, Y. Guo, B. Xu, K. Xu, Progress on complications of direct bypass for Moyamoya disease, Int. J. Med. Sci. 13 (8) (2016) 578–587.

[7] L. Zhang, K. Xu, Y. Zhang, X. Wang, J. Yu, Treatment strategies for aneurysms associated with moyamoya disease, Int. J. Med. Sci. 12 (3) (2015) 234–242.
[8] J.L. Yu, H.L. Wang, K. Xu, Y. Li, Q. Luo, Endovascular treatment of intracranial aneurysms associated with moyamoya disease or moyamoya syndrome, Interv. Neuroradiol. 16 (3) (2010) 240–248.
[9] T. Iwama, T. Todaka, N. Hashimoto, Direct surgery for major artery aneurysm associated with moyamoya disease, Clin. Neurol. Neurosurg. 99 (Suppl. 2) (1997) S191–S193.
[10] T. Ji, K. Hou, C. Li, J. Yu, Imaging features of internal maxillary artery and extracranial middle meningeal artery and their relationships on head CTA, Neuroradiol. J. 34 (6) (2021) 629–641.
[11] K. Hou, T. Ji, T. Luan, J. Yu, CT angiographic study of the cerebral deep veins around the vein of Galen, Int. J. Med. Sci. 18 (7) (2021) 1699–1710.
[12] K. Houkin, N. Nakayama, S. Kuroda, T. Nonaka, T. Shonai, T. Yoshimoto, Novel magnetic resonance angiography stage grading for moyamoya disease, Cerebrovasc. Dis. 20 (5) (2005) 347–354.
[13] T. Sugino, T. Mikami, S. Ohtaki, T. Hirano, S. Iihoshi, K. Houkin, et al., Assessment of moyamoya disease using multidetector row computed tomography, J. Stroke Cerebrovasc. Dis. 22 (5) (2013) 644–649.
[14] M. Ishikawa, S. Terao, H. Kagami, M. Inaba, H. Naritaka, Intralateral and Perilateral ventricular arteries on original axial magnetic resonance angiography in adult Moyamoya disease, Eur. Neurol. 84 (2) (2021) 119–123.
[15] Q. Li, L. Qu, Y. Yuan, B. Xu, Y. Guo, K. Xu, et al., Analysis of the clinical characteristics of hemorrhagic moyamoya disease in the Jilin province of northeastern China: a single-center study of 212 cases, Biomed. Rep. 8 (2) (2018) 191–197.
[16] M. Fukui, Guidelines for the diagnosis and treatment of spontaneous occlusion of the circle of Willis ('moyamoya' disease). Research committee on spontaneous occlusion of the circle of Willis (Moyamoya disease) of the Ministry of Health and Welfare, Japan, Clin. Neurol. Neurosurg. 99 (Suppl. 2) (1997) S238–S240.
[17] J. Suzuki, N. Kodama, Cerebrovascular "Moyamoya" disease. 2. Collateral routes to forebrain via ethmoid sinus and superior nasal meatus, Angiology 22 (4) (1971) 223–236.
[18] A.P. Huang, H.M. Liu, D.M. Lai, C.C. Yang, Y.H. Tsai, K.C. Wang, et al., Clinical significance of posterior circulation changes after revascularization in patients with moyamoya disease, Cerebrovasc. Dis. 28 (3) (2009) 247–257.
[19] M. Komiyama, Moyamoya disease is a vascular form of neurocristopathy: disease of the embryologic cephalic neural crest, Childs Nerv. Syst. 33 (4) (2017) 567–568.
[20] M. Komiyama, Moyamoya disease is a progressive occlusive Arteriopathy of the primitive internal carotid artery, Interv. Neuroradiol. 9 (1) (2003) 39–45.
[21] Y. Mineharu, Y. Takagi, A. Koizumi, T. Morimoto, T. Funaki, T. Hishikawa, et al., Posterior cerebral artery involvement in unilateral moyamoya disease is exclusively ipsilateral and influenced by RNF213 mutation gene dose: the SUPRA Japan study: PCA involvement in unilateral moyamoya, J. Stroke Cerebrovasc. Dis. 33 (2) (2024) 107513.
[22] S. He, X. Hao, Z. Liu, Y. Wang, J. Zhang, X. Wang, et al., Association between DIAPH1 variant and posterior circulation involvement with Moyamoya disease, Sci. Rep. 13 (1) (2023) 10732.
[23] S.S. Tigchelaar, A.R. Wang, S.D. Vaca, Y. Li, G.K. Steinberg, Incidence and outcomes of posterior circulation involvement in Moyamoya disease, Stroke 55 (5) (2024) 1254–1260, https://doi.org/10.1161/STROKEAHA.123.044693.
[24] S. Mugikura, S. Takahashi, S. Higano, R. Shirane, Y. Sakurai, S. Yamada, Predominant involvement of ipsilateral anterior and posterior circulations in moyamoya disease, Stroke 33 (6) (2002) 1497–1500.
[25] T. Hishikawa, K. Tokunaga, K. Sugiu, I. Date, Assessment of the difference in posterior circulation involvement between pediatric and adult patients with moyamoya disease, J. Neurosurg. 119 (4) (2013) 961–965.
[26] H.J. Seol, D.C. Shin, Y.S. Kim, E.B. Shim, S.K. Kim, B.K. Cho, et al., Computational analysis of hemodynamics using a two-dimensional model in moyamoya disease, J. Neurosurg. Pediatr. 5 (3) (2010) 297–301.
[27] N. Saeki, A.L. Rhoton Jr., Microsurgical anatomy of the upper basilar artery and the posterior circle of Willis, J. Neurosurg. 46 (5) (1977) 563–578.
[28] A.A. Zeal, A.L. Rhoton Jr., Microsurgical anatomy of the posterior cerebral artery, J. Neurosurg. 48 (4) (1978) 534–559.
[29] D.G. Hardy, D.A. Peace, A.L. Rhoton Jr., Microsurgical anatomy of the superior cerebellar artery, Neurosurgery 6 (1) (1980) 10–28.
[30] B.S. Pai, R.G. Varma, R.N. Kulkarni, S. Nirmala, L.C. Manjunath, S. Rakshith, Microsurgical anatomy of the posterior circulation, Neurol. India 55 (1) (2007) 31–41.
[31] C. Shrontz, M. Dujovny, J.I. Ausman, F.G. Diaz, J.E. Pearce, S.K. Berman, et al., Surgical anatomy of the arteries of the posterior fossa, J. Neurosurg. 65 (4) (1986) 540–544.
[32] S. Hara, J. Kikuta, K. Takabayashi, K. Kamagata, S. Hayashi, M. Inaji, et al., Decreased diffusivity along the perivascular space and cerebral hemodynamic disturbance in adult moyamoya disease, J. Cereb. Blood Flow Metab. (2024), https://doi.org/10.1177/0271678X241245492, 271678x241245492.
[33] K. Onodera, H. Ooigawa, S. Tabata, T. Kimura, M. Lepic, K. Suzuki, et al., Effect of revascularization surgery on cerebral hemodynamics in adult moyamoya disease, Clin. Neurol. Neurosurg. 239 (2024) 108180.