RESEARCH ARTICLE OPEN ACCESS

Noninvasive Assessment of the Risk Features of Hemorrhage in Moyamoya Disease Using 7T MRI

Qi Duan,[1,*] Jinhao Lyu,[1,*] Ziqi Liu,[2,*] Fangbin Hao,[3] Runze Li,[1] Simeng Liu,[3] Xiaokuan Hao,[2] Jingjie Li,[3] Xianbing Bian,[1] Caohui Duan,[1] Song Wang,[1] Wanbing Wang,[1] Rong Wang,[2] Lian Duan,[3,†] and Xin Lou[1,†]

Neurology® 2025;104:e213617. doi:10.1212/WNL.0000000000213617

Correspondence
Dr. Lou
louxin@301hospital.com.cn
or Dr. L. Duan
duanlian307@sina.com

Abstract

Background and Objectives

While digital subtraction angiography (DSA) is traditionally used for moyamoya disease (MMD) assessment, its invasiveness and limitations necessitate alternative methods. The higher signal-to-noise ratio (SNR) and contrast-to-noise ratio of 7T MRI improve the clarity of the image and retains the details of the structures. We aimed to assess the performance of 7T MRI in identifying hemorrhagic risk features of MMD compared with 3T MRI and DSA.

Methods

This cross-sectional study recruited patients with MMD who underwent both 7T and 3T MRI scans within a 24-hour window, from March 2022 to December 2023. Patients were categorized into hemorrhagic, ischemic, and asymptomatic groups based on standard MRI findings and clinical symptoms. Corresponding DSA images acquired within 90 days were also collected as a comparative benchmark. Hemorrhage risk factors including dilatation and branch extension of the anterior choroidal artery (AChA) and posterior communicating artery (PComA) were assessed and graded on time-of-flight magnetic resonance angiography (TOF-MRA) and DSA images following established protocols. The hemorrhage locations were classified into anterior and posterior circulation groups.

Results

A total of 180 patients (mean age, 43.95 ± 11.02 [SD] years; 53.9% female) were included in the study (hemorrhagic = 51, ischemic = 37, asymptomatic = 92). Notably, 42.4% of AChA and 27.7% of PComA anomalies detected on 7T TOF-MRA were absent on 3T imaging. The 7T TOF-MRA demonstrated a strong correlation with DSA in assessing the AChA stage (weighted $\kappa = 0.891$, $p < 0.001$) and PComA stage (weighted $\kappa = 0.761$, $p < 0.001$). Higher AChA (70.6% vs 21.6% vs 6.5%, $p < 0.001$) and PComA (51.0% vs 8.1% vs 12.0%, $p < 0.001$) grades were more common in patients with hemorrhagic MMD compared with ischemic and asymptomatic groups. In binary logistic regression analysis for hemorrhagic and ischemic groups, elevated stages of AChA (odds ratio [OR] 1.90, 95% CI 1.20–3.54, $p = 0.042$) and PComA (OR 3.89, 95% CI 1.76–8.58, $p = 0.001$) were associated with increased hemorrhagic risk. Furthermore, the proportion of higher AChA (62.2%, $p = 0.008$) and PComA (51.3%, $p = 0.010$) grades were more prevalent in cases involving both anterior and posterior circulations.

Discussion

The 7T TOF-MRA visualization of dilatation and branching extension of the AChA and PComA indicates a heightened risk of hemorrhage, suggesting that this imaging technique could serve as a valuable noninvasive tool for identifying hemorrhagic vulnerabilities in MMD.

MORE ONLINE

Supplementary Material

Class of Evidence
Criteria for rating therapeutic and diagnostic studies
NPub.org/coe

*These authors contributed equally to this work as co-first authors.

†These authors contributed equally to this work as co-corresponding authors.

[1]Department of Radiology, the First Medical Center of Chinese PLA General Hospital, Beijing, China; [2]Department of Neurosurgery, Beijing Tiantan Hospital, Capital Medical University, China; and [3]Department of Neurosurgery, the First Medical Center of Chinese PLA General Hospital, Beijing, China.

Glossary

AChA = anterior choroidal artery; **DSA** = digital subtraction angiography; **FLAIR** = fluid-attenuated inversion recovery; **MMD** = moyamoya disease; **MRA** = magnetic resonance angiography; **OR** = odds ratio; **PComA** = posterior communicating artery; **SNR** = signal-to-noise ratio; **SWI** = susceptibility-weighted imaging; **TOF-MRA** = time-of-flight magnetic resonance angiography.

Trial Registration Information

ClinicalTrials.gov, NCT05287750, Brain Diseases on 7.0T Magnetic Resonance Imaging, First Submitted January 2022. clinicaltrials.gov/study/NCT05287750.

Classification of Evidence

This study provides Class II evidence that 7T-TOF MRA accurately distinguishes hemorrhagic risk in patients with MMD compared with 3T-TOF MRA and DSA.

Introduction

Moyamoya disease (MMD) is a chronic cerebrovascular disease characterized by progressive steno-occlusion of the internal carotid arteries and compensatory development of a "puff of smoke" collateral network.[1-3] It is a leading cause of stroke in pediatric and young patients.[4] Conventional digital subtraction angiography (DSA) is considered the gold standard for MMD diagnosis and evaluation.[5] However, DSA is an invasive procedure that is always not feasible for pediatric patients and is unnecessary when internal carotid artery occlusion (bottle neck sign) and moyamoya vessels are found by magnetic resonance angiography (MRA).[6]

MMD with hemorrhagic stroke is associated with a high rate of disability and even mortality.[7] The dilatation and branch extension of the anterior choroidal artery (AChA) and posterior communicating artery (PComA) are recognized as potent predictors of hemorrhage.[8] While previous research has considered computed tomographic angiography as an alternative to DSA for assessing PComA and AChA,[9] the need for periodic examination in patients with MMD and the established dose-response relationship between CT-related radiation exposure and brain cancer in young populations call for a more suitable diagnostic and follow-up method.[10,11]

MRI is an essential modality in MMD assessment, and hemorrhage risk factor may be identified. Time-of-flight MRA (TOF-MRA) is a prevalent noninvasive imaging technique that foregoes contract agent injection. With enhanced signal-to-noise ratio (SNR) and prolonged T1 relaxation time, 7.0T TOF-MRA of ultra-high-field strength offers a substantial imaging advantage for small vessels.[12-15] Compared with 1.5T and 3T MRA, 7T TOF-MRA enables the visualization of the smaller distal intracranial vessels, even the "puff of smoke" collateral network in MMD.[16]

To our knowledge, only a limited number of studies with small cohorts have delved into the clinical utility of 7T TOF-MRA for patients with MMD.[17-19] Therefore, this study aims to systematically assess the performance of 7T MRI in identifying hemorrhagic risk features of MMD compared with 3T MRI and DSA.

Methods

Patients

We analyzed data from an observational study, which recruited patients with MMD from our hospital from March 2022 to December 2023. This study is based on an East Asian cohort of Chinese ethnicity. Patients who underwent both 7T and 3T TOF-MRA examinations within 24 hours from March 2022 to December 2023 were recruited. DSA images were also collected if the interval time between DSA and MRA was less than 3 months. Detailed inclusion and exclusion criteria are delineated in Figure 1.

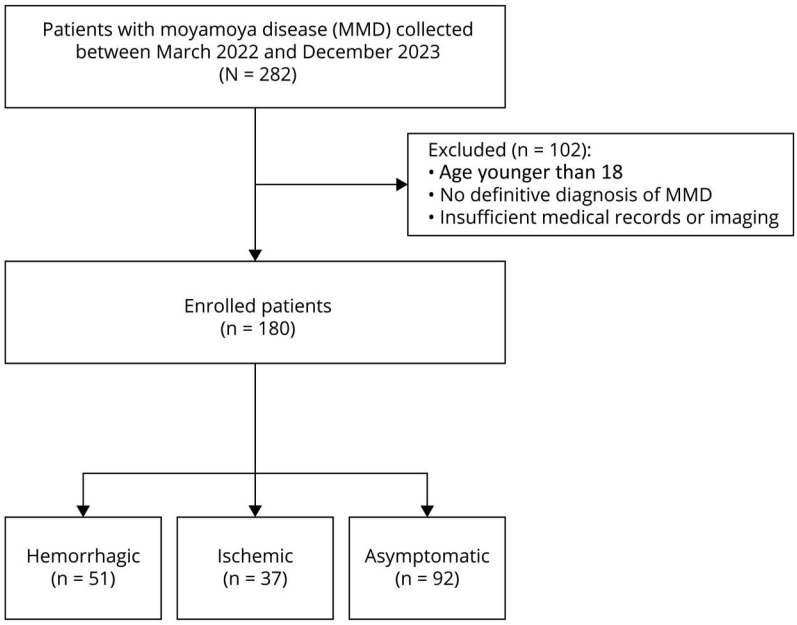
Standard Protocol Approvals, Registrations, and Patient Consents

Written informed consent was obtained from all patients (or guardians of participants) in the study. This study was approved by the local ethics committees of the participating institutions (S2021-541). This study is registered at ClinicalTrials.gov: NCT05287750.

Clinical Protocol

Clinical characteristics including age, sex, medical history of hypertension, diabetes mellitus, hyperlipidemia, smoking, and alcohol status were documented. Patients diagnosed with MMD by DSA and MRI according to the statement published in 2022 were included in this study.[20] The type of MMD was stratified into hemorrhagic, ischemic, and asymptomatic categories, integrating patient-reported symptoms, medical history, and imaging findings.[21] Patients with MMD who

Figure 1 Flow Diagram



experienced intracranial hemorrhage but without cerebral infarction or transient ischemic attacks were classified into the hemorrhagic group. Likewise, patients with MMD who suffered from cerebral infarction or transient ischemic attacks but without intracranial hemorrhage were classified into the ischemic group. In addition, patients with MMD with other neurologic symptoms such as headaches, neurocognitive impairment, and secondary movement disorders but without stroke event were grouped into the asymptomatic group.

MRI Protocol

The 7T examinations were performed on a whole-body 7T MR scanner (MAGNETOM Terra; Siemens Healthcare, Erlangen, Germany) equipped with an 8-channel transmit and 32-channel receiving head coil. 3T examinations were performed on a 3T whole-body MR scanner (Discovery MR750; General Electric, Milwaukee, WI) equipped with an 8-channel receiving head coil. The 3-dimensional (3D) TOF-MRA imaging parameters at 7T were as follows: repetition time 23.0 milliseconds, echo time 3.42 milliseconds, voxel size 0.3 × 0.3 × 0.3 mm^3, flip angle 24°, and acquisition time 4 minutes 52 seconds. The imaging parameters at 3T, using clinical routine 3D TOF-MRA, were as follows: repetition time 20.0 milliseconds, echo time 2.1 milliseconds, voxel size 0.75 × 0.94 × 1.4 mm^3, flip angle = 15°, and acquisition time 3 minutes 12 seconds. The 7T parameters of T2 were as follows: repetition time 7,000.0 milliseconds, echo time 56.0 milliseconds, voxel size 0.2 × 0.2 × 0.2 mm^3, and flip angle 120°; those of T2 fluid-attenuated inversion recovery (FLAIR) were as follows: repetition time 9,000.0 milliseconds, echo time 75.0 milliseconds, voxel size 0.7 × 0.7 × 2.0 mm^3, and flip angle 120°; those of susceptibility-weighted imaging (SWI) were as follows: repetition time 21.0 milliseconds, echo time 14.0 milliseconds, voxel size 0.2 × 0.2 × 1.5 mm^3, and flip angle 10°.

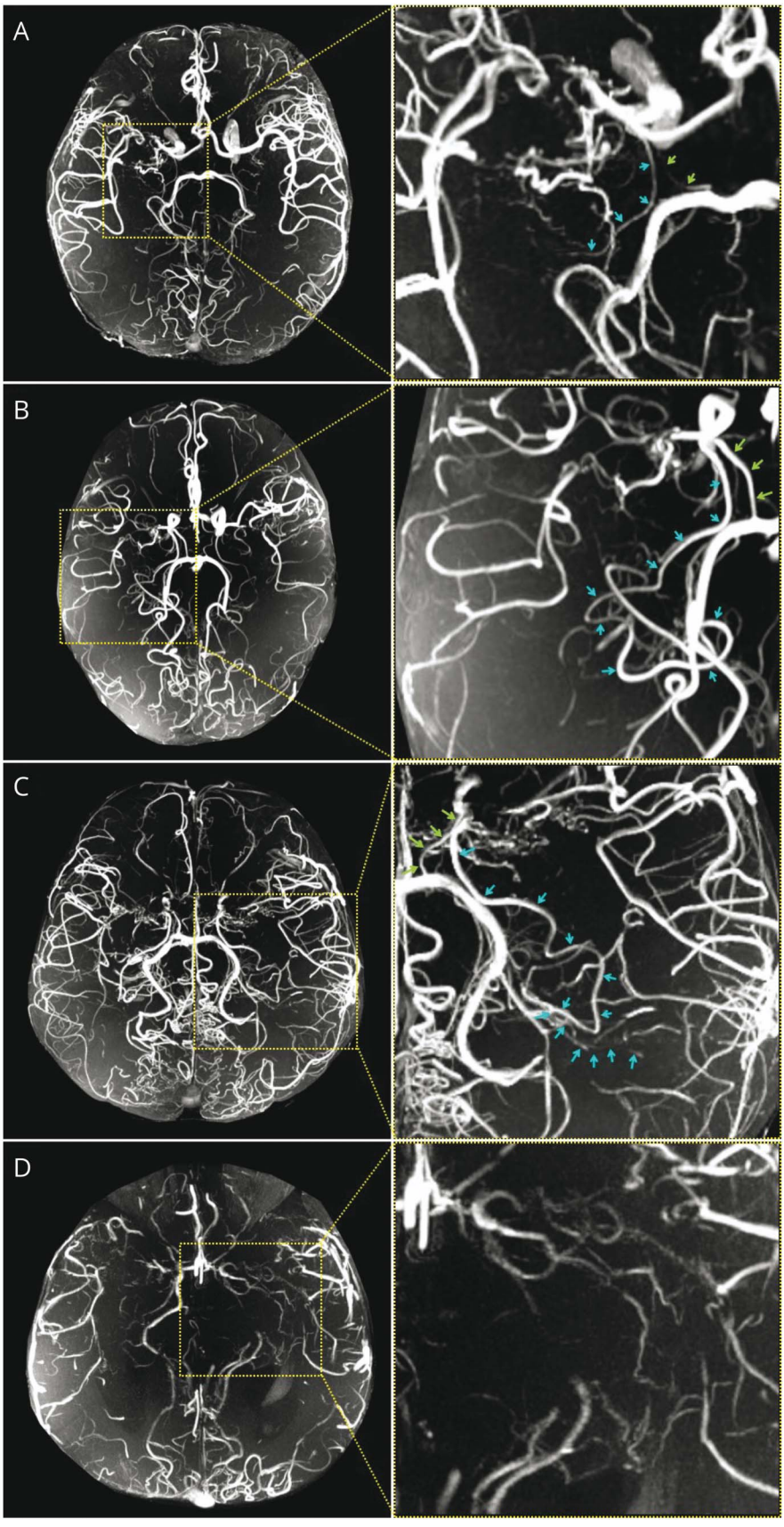
Image Assessment

All the images were assessed by 2 neuroradiologists with blinded clinical information (with 10 and 9 years of experience in neuroradiology). All the stages were based on maximum intensity projection of 7T TOF-MRA, 3T TOF-MRA, and DSA. Both the PComA stage and AChA stage were rated from 0 to 3 following an established protocol validated in a previous study.[22] AChA stages are as follows: grade 0, invisible or normal; grade 1, dilatation and extension within the choroidal fissure of AChA; grade 2, dilatation and extension beyond the choroidal fissure of AChA; grade 3, disappearance of AChA due to internal carotid artery occlusion. PComA stages are as follows: grade 0, invisible or normal; grade 1, dilatation without abnormal extensive branches of PComA; grade 2, dilatation with abnormal extensive branch of PComA; grade 3, disappearance of PComA due to internal carotid artery occlusion (eTable 1 and Figure 2). For comparative analysis of 7T TOF-MRA, 3T TOF-MRA, and DSA, in grade 0, we recorded specifically whether the AChA and PComA were invisible on the images. Besides, the AChA and PComA stages were applied on each MMD hemisphere for comparative analysis of 7T TOF-MRA, 3T TOF-MRA, and DSA, with the stage of the higher grade hemisphere recorded as the final stage of the patient. In the hemorrhagic group, additional data were recorded, including cerebral microbleeds (as detected by SWI), as well as the hemorrhagic location (classified as anterior or posterior based on T2/T2 FLAIR and SWI findings).

Statistical Analysis

All statistical analyses were performed using SPSS (version 26.0) and Medcalc (version 19.6.4). Continuous variables are

Figure 2 Assessing Method of AChA and PComA Stages



(A) Grade 0: AChA invisible or normal (blue arrows); PComA, invisible or normal (green arrows). (B) Grade 1: AChA dilatation and extension within the choroidal fissure (blue arrows); PComA dilatation without abnormal extensive branches (green arrows). (C) Grade 2: AChA dilatation and extension beyond the choroidal fissure (blue arrows); PComA dilatation with abnormal extensive branches (green arrows). (D) Grade 3: AChA disappearance due to internal carotid artery occlusion (blue arrows); PComA disappearance due to internal carotid artery occlusion (green arrows). AChA = anterior choroidal artery; PComA = posterior communicating artery.

presented as means ± SD. Categorical variables are reported as proportions and percentages. To assess the differences among 7T, 3T, and DSA pairwise, we used the weighted κ test when comparing the AChA stage and PComA stage. The κ values were interpreted as follows: less than 0.2 indicates poor agreement, 0.2 to 0.4 signifies fair agreement, 0.41 to 0.6 denotes moderate agreement, 0.61 to 0.8 represents good agreement, and 0.81 to 1.0 reflects perfect agreement. The evaluation of PComA stages, AChA stages, and the difference between the hemorrhagic group and other groups was performed using the Cohen κ test. The χ^2 test was used to compare PComA and AChA occurrences among ischemia, hemorrhage, and asymptomatic groups, based on 7T TOF-MRA findings. The Fisher exact test was performed as an alternative to the χ^2 test of independence when 1 or more of the cell counts in a 2 × 2 table was less than 5. Binary logistic regression was applied to analyze the independent factors associated with hemorrhage. Adjustment factors included age, sex, PComA stages, and AChA stages, chosen for their crucial role in clinical relating with hemorrhage in MMD. Interobserver agreement on assessing the AChA stage and PComA stage based on 7T TOF-MRA and 3T TOF-MRA between 2 readers was quantified using the intraclass correlation coefficient (<0.5, poor reliability; 0.5–0.75, moderate reliability; 0.75–0.9, good reliability; 0.9–1.0, excellent reliability). p Values were 2-sided, and those less than 0.05 were considered statistically significant.

Data Availability

Supporting data of this study are available from the corresponding author on reasonable request.

Results

Demographics and General Characteristics

A total of 355 hemispheres from 180 patients with MMD were analyzed, as illustrated in Figure 1. The average age was 43.95 ± 11.02 years, with 83 (46.1%) being male. The distribution of cases was as follows: 51 hemorrhagic (28.3%), 37 ischemic (21.6%), and 92 asymptomatic (51.1%). Detailed baseline characteristics are provided in Table 1.

Comparison Among 7T TOF-MRA and 3T TOF-MRA

There were statistical differences between 7T and 3T on displaying the AChA stage (weighted κ = 0.301, $p < 0.001$) and PComA stage (weighted κ = 0.399, $p < 0.001$). As for visibility comparison, 7T TOF-MRA presented AChA in 153 hemispheres (45.7%) and PComA in 115 hemispheres (32.4%) of a total of 355 hemispheres while 3T only presented AChA in 11 hemispheres (3.3%) and PComA in 22 hemispheres (6.2%). 7T outperformed 3T in presenting AChA (45.7% vs 3.3%) and PComA (32.4% vs 6.2%). Notably, approximately 42.4% of AChA and 27.7% of PComA anomalies identified on 7T TOF-MRA were not visualized on 3T (eTable 2). The results of interobserver assessment were good to excellent, as provided in eTable 3.

Comparison Among 7T TOF-MRA, 3T TOF-MRA, and DSA

We selected 70 hemispheres from 37 patients who underwent both 7T and 3T TOF-MRA examinations within 24 hours and DSA examination within 3 months (Table 1). The 7T TOF-MRA demonstrated a strong correlation with DSA in assessing AChA stage (weighted κ = 0.891, $p < 0.001$) and PComA stage (κ = 0.761, $p < 0.001$) (Figure 3). The correlation between 3T TOF-MRA and DSA was moderate for both AChA stage and PComA stage (weighted κ = 0.262, $p < 0.001$ and weighted κ = 0.221, $p < 0.001$) (Figures 4 and 5, eTable 4).

Risk Factors of Hemorrhage in MMD Based on 7T TOF-MRA

No significant differences were observed in patients' background demographics or the frequency of risk factors of stroke among the asymptomatic, ischemic, and hemorrhagic groups (Table 1). Higher AChA and PComA grades were more common in patients with hemorrhagic MMD ($p < 0.001$) (Table 1 and Figure 3). After adjustment, in binary logistic regression analysis for hemorrhagic and ischemic groups, an increased hemorrhagic risk was associated with higher grade shift in AChA (odd ratio [OR] 1.90, 95% CI 1.20–3.54, $p = 0.042$) or PComA (OR 3.89, 95% CI 1.76–8.58, $p = 0.001$) stages (Table 2). In binary logistic regression analysis for hemorrhagic and asymptomatic groups, an increased hemorrhagic risk was associated with higher grade shift in AChA (OR 4.41, 95% CI 2.43–7.99, $p < 0.001$) (Table 2).

Analysis in Hemorrhagic Hemispheres

In the analysis of 76 hemorrhagic hemispheres from 51 patients, higher grades of AChA (62.2%, $p = 0.008$) and PComA (51.3%, $p = 0.010$) were more frequently observed when both anterior and posterior circulations were affected (eTable 5).

Classification of Evidence

This study provides Class II evidence that 7T-TOF MRA accurately distinguishes hemorrhagic risk in patients with MMD compared with 3T-TOF MRA and DSA.

Discussion

In this study, we evaluated the efficacy of 7T TOF-MRA in grading the PComA and AChA. At equivalent imaging quality, 7T TOF-MRA demonstrates significantly superior visualization of the PComA and AChA compared to 3T ($p < 0.001$). In addition, 7T TOF-MRA demonstrated a strong correlation with DSA in identifying the characteristic features of MMD-related vasculature.

Although rare, MMD is a global disease and the most common reason that leads to stroke and transient ischemic attacks in children and adolescents.[3,4,23,24] The pathology of MMD is complex, involving genetic and environmental factors.[25-27] The primary changes in stenotic large vessels

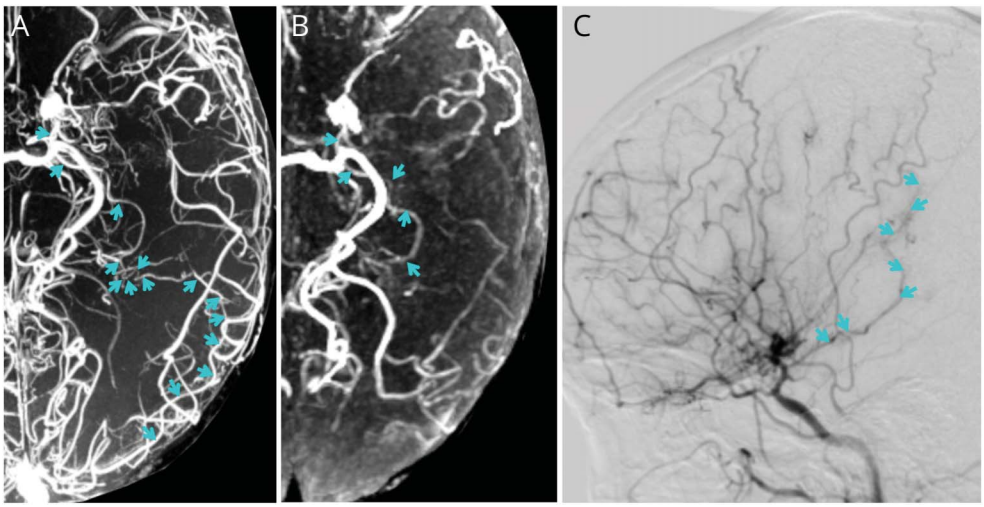
Table 1 Comparison of Baseline Characteristics Among Ischemic, Hemorrhagic, and Asymptomatic Groups

Characteristics	All	Hemorrhage	Ischemia	Asymptomatic	*p* Value
No. of patients	180	51	37	92	—
Age, y, mean ± SD	43.95 ± 11.02	44.76 ± 11.72	43.22 ± 10.02	43.79 ± 11.08	0.347
Male sex, n (%)	83 (46.1)	22 (43.1)	14 (37.8)	47 (51.1)	0.462
Hypertension, n (%)	78 (43.3)	27 (52.9)	17 (45.9)	34 (37.0)	0.170
Diabetes mellitus, n (%)	33 (18.3)	12 (23.5)	7 (18.9)	14 (15.2)	0.467
Hyperlipidemia, n (%)	49 (27.2)	12 (23.5)	14 (37.8)	23 (25.0)	0.261
Smoking, n (%)	32 (17.8)	8 (15.7)	7 (18.9)	17 (18.5)	0.897
Alcohol, n (%)	48 (26.7)	11 (21.6)	10 (27.0)	27 (29.3)	0.601
AChA stage, n (%)					<0.001
0	84 (46.7)	8 (15.7)	15 (40.5)	61 (66.3)	
1	46 (25.6)	7 (13.7)	14 (37.8)	25 (27.2)	
2	39 (21.7)	29 (56.9)	6 (16.2)	4 (4.3)	
3	11 (6.1)	7 (13.7)	2 (5.4)	2 (2.2)	
PComA stage, n (%)					<0.001
0	76 (42.2)	8 (15.7)	20 (54.1)	48 (52.2)	
1	64 (35.6)	17 (33.3)	14 (37.8)	33 (35.9)	
2	34 (18.9)	21 (41.2)	3 (8.1)	10 (10.9)	
3	6 (3.3)	5 (9.8)	0	1 (1.1)	

Abbreviations: AChA = anterior choroidal artery; PComA = posterior communicating artery; P1 value = results between hemorrhagic and ischemic patients; P2 value = results between hemorrhagic and asymptomatic patients; P3 value = results between ischemic and asymptomatic patients.
AChA and PComA stages were based on 7T MRI.

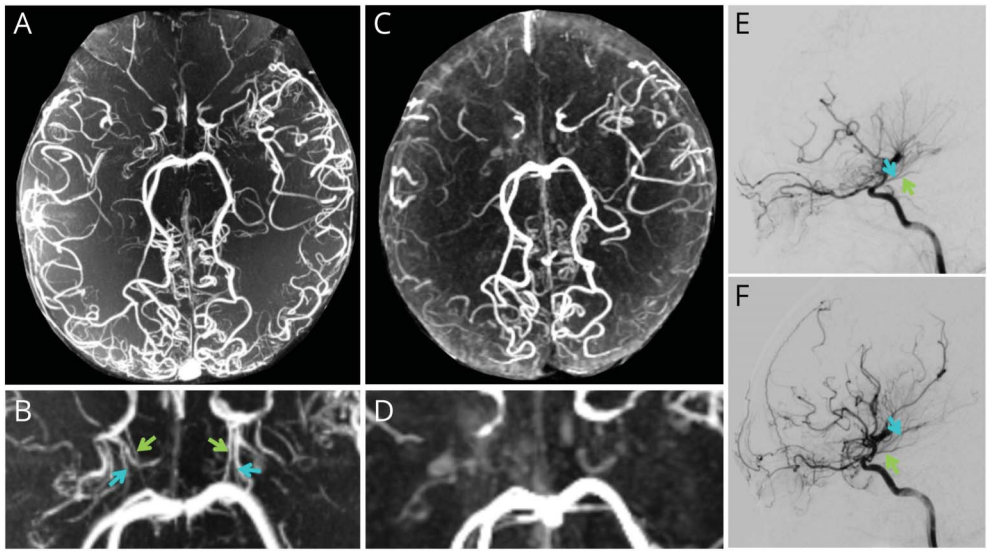
include intima fibrocellular thickening, internal elastic lamina irregular undulation, and outer diameter decrease, without signs of inflammation or atherosclerosis.[28] Neonatal moyamoya vessels typically exhibit a thin media and fragmented elastic lamina, which heightens the risk of rupture and intracranial hemorrhage.[27]

Figure 3 Comparison Between 7T TOF-MRA, 3T TOF-MRA, and DSA in the Visualization of the Anterior Choroidal Artery



(A–C) 7T TOF-MRA, 3T TOF-MRA, and DSA images of a patient with moyamoya disease. 7T TOF-MRA demonstrated superior performance to 3T while achieving comparable visualization of the left anterior choroidal artery (blue arrows) to DSA. DSA = digital subtraction angiography; TOF-MRA = time-of-flight magnetic resonance angiography.

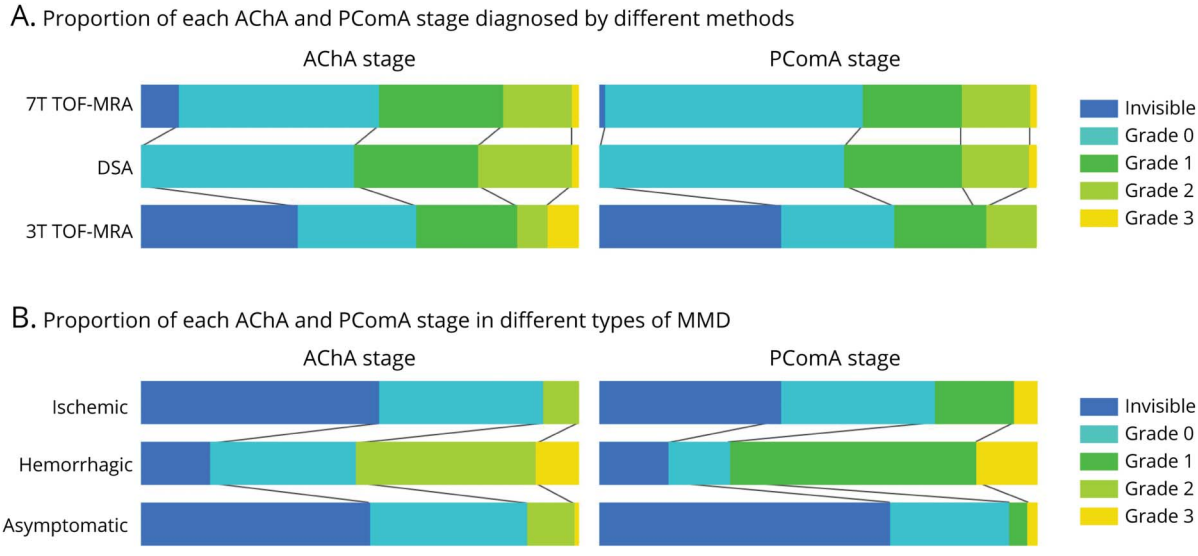
Figure 4 Comparison Between 7T TOF-MRA, 3T TOF-MRA, and DSA in the Visualization of the Anterior Choroidal Artery and Posterior Communicating Artery



TOF-MRA images of 7T (A and B) and 3T (C and D) and DSA images (E and F) of a patient with moyamoya disease. 7T TOF-MRA demonstrated superior performance to 3T and provided comparable visualization of both the anterior choroidal artery (blue arrows) and posterior communicating artery (green arrows) relative to DSA. DSA = digital subtraction angiography; TOF-MRA = time-of-flight magnetic resonance angiography.

MMD has long been a disease of unknown etiology because of a diagnostic procedure that excludes all other possible cerebrovascular diseases.[29] DSA was acknowledged as the gold standard for the diagnosis and evaluation of MMD and was used to identify and avoid transdural collaterals before surgery to decrease perioperative stroke risk because of its superior spatial resolution.[5] Follow-up is needed throughout patients' lives; however, DSA yields more than 6 times the cost relative to MRI per patient and needs more human resources.[30] Advances in MRA techniques have positioned itself as a primary diagnostic tool, surpassing DSA in routine clinical use. The widespread adoption of MRI has led to an increase in the detection of asymptomatic MMD cases, particularly benefiting pediatric patients by avoiding radiation exposure, reducing costs, and eliminating complications associated with the invasive procedure.[31,32] The additional information provided by DSA is inconvincible to justify the increased complication risk by invasive operation, cost, and time.[33] A better method used for diagnosis and follow-up in patients with MMD was explored by researchers.[9] While DSA remains

Figure 5 Comparison of Proportion of Each AChA and PComA Stage



AChA = anterior choroidal artery; DSA = digital subtraction angiography; MMD = moyamoya disease; PComA = posterior communicating artery; TOF-MRA = time-of-flight magnetic resonance angiography.

Table 2 Logistic Regression Analysis of Factors Associated With Different Types of Moyamoya Disease

	Crude			Adjusted		
Variable	**Crude OR**	**95% CI**	***p* Value**	**Adjusted OR**	**95% CI**	***p* Value**
Hemorrhagic and ischemic						
Age	1.01	0.97–1.05	0.513	1.04	0.99–1.09	0.119
Sex	0.80	0.34–1.91	0.618	0.45	0.15–1.39	0.164
AChA stage	2.64	1.57–4.42	<0.001	1.90	1.02–3.54	0.042
PComA stage	4.18	2.15–8.11	<0.001	3.89	1.76–8.58	0.001
Hemorrhagic and asymptomatic						
Age	1.01	0.98–1.04	0.621	1.01	0.97–1.05	0.601
Sex	1.38	0.69–2.74	0.304	0.82	0.33–2.50	0.667
AChA stage	5.30	3.15–8.93	<0.001	4.41	2.43–7.99	<0.001
PComA stage	3.45	2.12–5.60	<0.001	1.63	0.87–3.07	0.131

Abbreviations: AChA = anterior choroidal artery; CI = confidence interval; OR = odds ratio; PComA = posterior communicating artery.

a critical preoperative examination,[34] the advent of 7T MRI has introduced a potential shift. A previous study compared 7T and 3T MRI in patients with MMD, and their results indicated that 7T MRA is superior to 3T on detecting the abnormal vascular network in the basal ganglia.[16] In the past years, researchers[35] found that 7T TOF-MRA could be used to detect ventricular microaneurysms in collateral vessels of MMD, which is inaccessible by conventional imaging techniques. In their further research on 7T MRI in MMD, they[19] verified the excellent ability of 7T TOF-MRA in delineating deeply seated collateral networks of MMD.[19,35] However, research studies mentioned above have the same limitation of small sample size. The higher SNR and contrast-to-noise ratio of 7T TOF-MRA enable the clear depiction of small perforating arteries, which are often not visible on 3T.[12,13,36] Our study confirmed in a large cohort that 7T TOF-MRA can visualize the anastomoses of AChA (Figure 5) and provide comparable diagnostic quality of DSA in assessing AChA and PComA.

Previous studies demonstrated that hemorrhagic MMD is more common in adult patients, potentially leading to disability or death, and carries a high risk of recurrence.[8,37] Branches of the AChA and PComA supply blood to critical brain regions, including the periventricular, basal ganglia, and thalamus, and hemorrhage in these branches can lead to severe neurologic symptoms. Thus, early identification of hemorrhagic risk factors is crucial. The Japan Adult Moyamoya Trial demonstrated that bypass surgery is more effective than nonsurgical treatment in preventing rebleeding.[38] The improvement of the dilatation and extension of AChA and PComA has been proven to be associated with a low rebleeding rate after combined revascularization surgery.[39] In addition, improved dilated branches of AChA and PComA could reduce the ipsilateral rebleeding rate.[40] The angiographic dilatation of the AChA and PComA may hint hemodynamic change in these vessels to compensate the decrease of brain blood supply; however, increased blood flow and pressure could lead to rupture of fragile moyamoya vessels, which is a suspected cause of hemorrhage.[41] Previous studies have demonstrated that dilatation of the AChA and PComA may serve as collateral channels, supplying dilatation perforating arteries and showing a strong association with intracranial hemorrhage in patients with MMD.[42,43] Therefore, the AChA and PComA play a crucial role in hemorrhage prediction in MMD. Our study also explored the differences in PComA and AChA between ischemic and hemorrhagic patients, finding that hemorrhagic patients had a higher rate of dilatation or branch extension. Our results showed that 7T can recognize 42.4% more AChA anomalies and 27.7% more PComA anomalies than 3T, which may aid in clinical decision making.

Our study had several limitations. First, because patients with MMD could be diagnosed by MRI directly, only a limited subset of patients received DSA in conjunction with MRI. Second, this investigation was a cross-sectional design; future longitudinal cohort studies would be valuable to further validate our findings. Third, our focus was primarily on the assessment of the AChA and PComA; however, other critical imaging characteristics, such as the development of collateral patterns and microaneurysms, also play a pivotal role in the context of MMD. However, these aspects need modifications and optimizations of our protocols to improve the performance in visualization and warrant further investigation in our subsequent research endeavors. Finally, our study is based on an Asian cohort, which may limit the generalizability of our results to non–East Asian populations. Our future studies would aim to include diverse ethnic groups to enhance the external validity of the findings.

In conclusion, 7T TOF-MRA surpasses 3T TOF-MRA in visualization of PComA and AChA and correlates strongly with DSA findings. The marked dilatation and abnormal branching of AChA and PComA observed on 7T MRA are indicative of hemorrhagic MMD. The noninvasive nature of 7T TOF-MRA, coupled with its lack of intravenous contrast and ionizing radiation, significantly minimizes complication risks, especially for pediatric and contrast-allergic patients, making it a viable alternative to DSA for diagnosing MMD and identifying patients at risk of hemorrhage.

Author Contributions

Q. Duan: drafting/revision of the manuscript for content, including medical writing for content; major role in the acquisition of data; study concept or design; analysis or interpretation of data. J. Lyu: drafting/revision of the manuscript for content, including medical writing for content; major role in the acquisition of data; study concept or design; analysis or interpretation of data. Z. Liu: major role in the acquisition of data. F. Hao: major role in the acquisition of data. R. Li: major role in the acquisition of data. S. Liu: major role in the acquisition of data. X. Hao: major role in the acquisition of data. J. Li: major role in the acquisition of data. X. Bian: major role in the acquisition of data. C. Duan: major role in the acquisition of data. S. Wang: major role in the acquisition of data. W. Wang: major role in the acquisition of data. R. Wang: major role in the acquisition of data. L. Duan: major role in the acquisition of data. X. Lou: drafting/revision of the manuscript for content, including medical writing for content; major role in the acquisition of data; study concept or design; analysis or interpretation of data.

Study Funding

This work was supported by the National Natural Science Foundation of China (grants 82327803 and 82441014 to X.L.; 82271952 to J.H.L.; 82171887 to R.W.; 82202133 to C.D.).

Disclosure

The authors report no relevant disclosures. Go to Neurology.org/N for full disclosures.

Publication History

Received by *Neurology*® August 12, 2024. Accepted in final form March 27, 2025. Submitted and externally peer reviewed. The handling editor was Editor-in-Chief José Merino, MD, MPhil, FAAN.

References

1. Suzuki J, Takaku A. Cerebrovascular "moyamoya" disease. Disease showing abnormal net-like vessels in base of brain. *Arch Neurol*. 1969;20(3):288-299. doi:10.1001/archneur.1969.00480090076012
2. Suzuki J, Kodama N. Moyamoya disease: a review. *Stroke*. 1983;14(1):104-109. doi:10.1161/01.str.14.1.104
3. Kim JS. Moyamoya disease: epidemiology, clinical features, and diagnosis. *J Stroke*. 2016;18(1):2-11. doi:10.5853/jos.2015.01627
4. Park EK, Lee YH, Shim KW, Choi JU, Kim DS. Natural history and progression factors of unilateral moyamoya disease in pediatric patients. *Childs Nerv Syst*. 2011;27(8):1281-1287. doi:10.1007/s00381-011-1469-y
5. Ferriero DM, Fullerton HJ, Bernard TJ, et al. Management of stroke in neonates and children: a scientific statement from the American Heart Association/American Stroke Association. *Stroke*. 2019;50(3):e51-e96. doi:10.1161/str.0000000000000183
6. Yasaka M, Ogata T, Yasumori K, Inoue T, Okada Y. Bottle neck sign of the proximal portion of the internal carotid artery in moyamoya disease. *J Ultrasound Med*. 2006;25(12):1547-1552; quiz 1553-1554. doi:10.7863/jum.2006.25.12.1547
7. Research Committee on the Pathology and Treatment of Spontaneous Occlusion of the Circle of Willis; Health Labour Sciences Research Grant for Research on Measures for Infractable Diseases Guidelines for diagnosis and treatment of moyamoya disease (spontaneous occlusion of the circle of Willis). *Neurol Med Chir (Tokyo)*. 2012;52(5):245-266. doi:10.2176/nmc.52.245
8. Morioka M, Hamada J, Kawano T, et al. Angiographic dilatation and branch extension of the anterior choroidal and posterior communicating arteries are predictors of hemorrhage in adult moyamoya patients. *Stroke*. 2003;34(1):90-95. doi:10.1161/01.str.0000047120.67507.0d
9. Guo X, Gao L, Yu H, et al. Computed tomographic angiography may be used for assessing the dilatation of the anterior choroidal and posterior communicating arteries in patients with moyamoya syndrome. *Eur Radiol*. 2021;31(8):5544-5551. doi:10.1007/s00330-021-07722-2
10. Hauptmann M, Byrnes G, Cardis E, et al. Brain cancer after radiation exposure from CT examinations of children and young adults: results from the EPI-CT cohort study. *Lancet Oncol*. 2023;24(1):45-53. doi:10.1016/s1470-2045(22)00655-6
11. Lyu J, Fu Y, Yang M, et al. Generative adversarial network-based noncontrast CT angiography for aorta and carotid arteries. *Radiology*. 2023;309(2):e230681. doi:10.1148/radiol.230681
12. Umutlu L, Theysohn N, Maderwald S, et al. 7 Tesla MPRAGE imaging of the intracranial arterial vasculature: nonenhanced versus contrast-enhanced. *Acad Radiol*. 2013;20(5):628-634. doi:10.1016/j.acra.2012.12.012
13. Trattnig S, Springer E, Bogner W, et al. Key clinical benefits of neuroimaging at 7T. *Neuroimage*. 2018;168:477-489. doi:10.1016/j.neuroimage.2016.11.031
14. Wang W, Lyu J, Wang X, et al. 7T MRI in cerebrovascular disorders: from large artery abnormalities to small vessel disease. *Meta-Radiology*. 2024;2(3):100085. doi:10.1016/j.metrad.2024.100085
15. Li R, Lyu J, Hu R, et al. Morphological study on lenticulostriate arteries in patients with middle cerebral artery stenosis at 7T MRI. *J Magn Reson Imaging*. Jan 9, 2025. Epub ahead of print. doi:10.1002/jmri.29693
16. Oh BH, Moon HC, Baek HM, et al. Comparison of 7T and 3T MRI in patients with moyamoya disease. *Magn Reson Imaging*. 2017;37:134-138. doi:10.1016/j.mri.2016.11.019
17. Dengler NF, Madai VI, Wuerfel J, et al. Moyamoya vessel pathology imaged by ultra-high-field magnetic resonance imaging at 7.0T. *J Stroke Cerebrovasc Dis*. 2016;25(6):1544-1551. doi:10.1016/j.jstrokecerebrovasdis.2016.01.041
18. Deng X, Zhang Z, Zhang Y, et al. Comparison of 7.0- and 3.0-T MRI and MRA in ischemic-type moyamoya disease: preliminary experience. *J Neurosurg*. 2016;124(6):1716-1725. doi:10.3171/2015.5.Jns15767
19. Matsushige T, Kraemer M, Sato T, et al. Visualization and classification of deeply seated collateral networks in moyamoya angiopathy with 7T MRI. *AJNR Am J Neuroradiol*. 2018;39(7):1248-1254. doi:10.3174/ajnr.A5700
20. Gonzalez NR, Amin-Hanjani S, Bang OY, et al. Adult moyamoya disease and syndrome: current perspectives and future directions: a scientific statement from the American Heart Association/American Stroke Association. *Stroke*. 2023;54(10):e465-e479. doi:10.1161/str.0000000000000443
21. Sun H, Li W, Xia C, et al. Angiographic and hemodynamic features in asymptomatic hemispheres of patients with moyamoya disease. *Stroke*. 2022;53(1):210-217. doi:10.1161/strokeaha.121.035296
22. Liu P, Han C, Li DS, Lv XL, Li YX, Duan L. Hemorrhagic moyamoya disease in children: clinical, angiographic features, and long-term surgical outcome. *Stroke*. 2016;47(1):240-243. doi:10.1161/strokeaha.115.010512
23. Kuroda S, Houkin K. Moyamoya disease: current concepts and future perspectives. *Lancet Neurol*. 2008;7(11):1056-1066. doi:10.1016/s1474-4422(08)70240-0
24. Grangeon L, Guey S, Schwitalla JC, et al. Clinical and molecular features of 5 European multigenerational families with moyamoya angiopathy. *Stroke*. 2019;50(4):789-796. doi:10.1161/strokeaha.118.023972
25. Bang OY, Chung JW, Kim SJ, et al. Caveolin-1, Ring finger protein 213, and endothelial function in Moyamoya disease. *Int J Stroke*. 2016;11(9):999-1008. doi:10.1177/1747493016662039
26. Shirozu N, Ohgidani M, Hata N, et al. Angiogenic and inflammatory responses in human induced microglia-like (iMG) cells from patients with Moyamoya disease. *Sci Rep*. 2023;13(1):14842. doi:10.1038/s41598-023-41456-z
27. Fang YC, Wei LF, Hu CJ, Tu YK. Pathological circulating factors in moyamoya disease. *Int J Mol Sci*. 2021;22(4):1696. doi:10.3390/ijms22041696
28. Yamashita M, Oka K, Tanaka K. Histopathology of the brain vascular network in moyamoya disease. *Stroke*. 1983;14(1):50-58. doi:10.1161/01.str.14.1.50
29. Kim JW, Hayashi T, Kim SK, Shirane R. Technical evolution of pediatric neurosurgery: moyamoya disease. *Childs Nerv Syst*. 2023;39(10):2819-2827. doi:10.1007/s00381-023-06017-9
30. Northam WT, Slingerland AL, Orbach DB, Smith ER. Magnetic resonance imaging/angiography versus catheter angiography for annual follow-up of pediatric moyamoya patients: a cost outcomes analysis. *Neurosurgery*. 2023;92(6):1243-1248. doi:10.1227/neu.0000000000002357
31. Willinsky RA, Taylor SM, TerBrugge K, Farb RI, Tomlinson G, Montanera W. Neurologic complications of cerebral angiography: prospective analysis of 2,899 procedures and review of the literature. *Radiology*. 2003;227(2):522-528. doi:10.1148/radiol.2272012071
32. Robertson RL, Chavali RV, Robson CD, et al. Neurologic complications of cerebral angiography in childhood moyamoya syndrome. *Pediatr Radiol*. 1998;28(11):824-829. doi:10.1007/s002470050474

33. Lou X, Ma X, Liebeskind DS, et al. Collateral perfusion using arterial spin labeling in symptomatic versus asymptomatic middle cerebral artery stenosis. *J Cereb Blood Flow Metab*. 2019;39(1):108-117. doi:10.1177/0271678x17725212
34. Nguyen VN, Parikh KA, Motiwala M, et al. Surgical techniques and indications for treatment of adult moyamoya disease. *Front Surg*. 2022;9:966430. doi:10.3389/fsurg.2022.966430
35. Matsushige T, Kraemer M, Schlamann M, et al. Ventricular microaneurysms in moyamoya angiopathy visualized with 7T MR angiography. *AJNR Am J Neuroradiol*. 2016;37(9):1669-1672. doi:10.3174/ajnr.A4786
36. Cheng K, Duan Q, Hu J, et al. Evaluation of postcontrast images of intracranial tumors at 7T and 3T MRI: an intra-individual comparison study. *CNS Neurosci Ther*. 2023;29(2):559-565. doi:10.1111/cns.14036
37. Fujimura M, Funaki T, Houkin K, et al. Intrinsic development of choroidal and thalamic collaterals in hemorrhagic-onset moyamoya disease: case-control study of the Japan Adult Moyamoya Trial. *J Neurosurg*. 2019;130(5):1453-1459. doi:10.3171/2017.11.Jns171990
38. Miyamoto S, Yoshimoto T, Hashimoto N, et al. Effects of extracranial-intracranial bypass for patients with hemorrhagic moyamoya disease: results of the Japan Adult Moyamoya Trial. *Stroke*. 2014;45(5):1415-1421. doi:10.1161/strokeaha.113.004386
39. Wang J, Yang Y, Li X, et al. Lateral posterior choroidal collateral anastomosis predicts recurrent ipsilateral hemorrhage in adult patients with moyamoya disease. *AJNR Am J Neuroradiol*. 2019;40(10):1665-1671. doi:10.3174/ajnr.A6208
40. Jiang H, Ni W, Xu B, et al. Outcome in adult patients with hemorrhagic moyamoya disease after combined extracranial-intracranial bypass. *J Neurosurg*. 2014;121(5):1048-1055. doi:10.3171/2014.7.Jns132434
41. Luo S, Zhan W, Zhang L, et al. Ischemic patterns and their angiographic risk factors in adult patients with moyamoya disease. *Ann Clin Transl Neurol*. 2023;10(12):2386-2393. doi:10.1002/acn3.51927
42. Morioka M, Hamada J, Todaka T, Yano S, Kai Y, Ushio Y. High-risk age for rebleeding in patients with hemorrhagic moyamoya disease: long-term follow-up study. *Neurosurgery*. 2003;52(5):1049-1054; discussion 1054-1055. doi:10.1227/01.neu.0000058223.73857.f4
43. Hori S, Kashiwazaki D, Yamamoto S, et al. Impact of interethnic difference of collateral angioarchitectures on prevalence of hemorrhagic stroke in moyamoya disease. *Neurosurgery*. 2019;85(1):134-146. doi:10.1093/neuros/nyy236