Original research

Magnetic resonance perfusion imaging findings following flow diversion in patients with complex middle cerebral artery bifurcation aneurysms: a single-center analysis regarding the jailed cortical branches

Bora Korkmazer ,[1] Ahmet Kursat Karaman ,[2] Ahmet Ustundag,[3] Serdar Arslan,[1] Osman Kızılkılıç,[1] Naci Koçer,[1] Civan Islak [1]

[1]Division of Neuroradiology, Department of Radiology, Istanbul University-Cerrahpasa, Cerrahpasa Faculty of Medicine, Istanbul, Turkey
[2]Department of Radiology, Sureyyapasa Chest Diseases and Chest Surgery Training and Research Hospital, Istanbul, Turkey
[3]Department of Radiology, Istanbul University-Cerrahpasa, Cerrahpasa Faculty of Medicine, Istanbul, Turkey

Correspondence to
Dr Bora Korkmazer, Neuroradiology, Istanbul University-Cerrahpasa, Cerrahpasa Faculty of Medicine, 34098 Istanbul, Turkey; borakorkmazer@gmail.com

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ABSTRACT

Background Flow diverter (FD) devices provide a safe and effective treatment option especially for wide-necked intracranial aneurysms. One of the main concerns in patients treated with FD devices is patency of arterial branches jailed by the stent. However, there are no long-term data from magnetic resonance perfusion (MRP) studies regarding jailed branches. In this study we aimed to reveal the MRP findings in patients with jailed middle cerebral artery (MCA) cortical branches during long-term follow-up after flow diversion.

Methods Patients who underwent FD stent treatment for MCA aneurysms with a resulting jailed cortical branch were included. Follow-up clinical, angiographic, and MRP examination findings were recorded. Different MRP parameters were measured in the MCA territory regarding the jailed branches.

Results Eighteen patients treated endovascularly with flow diversion for a total of 20 MCA aneurysms were included. At angiographic follow-up (median 35 months, range 7–95 months) complete occlusion was observed in 13 (65%) aneurysms and partial occlusion was observed in 6 (30%). The mean transit time (MTT) prolongation, MTT ratio, time-to peak (TTP) prolongation, and TTP ratio were 1.34, 1.20, 1.18, and 1.06 s, respectively, when compared with the contralateral side in the MCA territory. MTT, TTP, and cerebral blood volume values of the patients showed statistically significant differences compared with the contralateral side ($P<0.05$).

Conclusions Flow diversion treatment of complex bifurcation aneurysms can be effective and safe. MRP examination may reveal perfusion changes in the territory vascularized via a jailed branch, and these changes are rarely accompanied by clinical findings.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Flow-diverter (FD) stents are an effective and safe treatment option, especially in the treatment of wide-necked intracranial aneurysms. One of the major concerns regarding the use of an FD stent is the fate of the side branches covered by the stent and the hemodynamic changes in the territory supplied by these side branches.

WHAT THIS STUDY ADDS

⇒ The present study reveals long-term magnetic resonance perfusion (MRP) changes (particularly mean transit time (MTT), time-to-peak, and relative cerebral blood volume) in the territory fed by the jailed branch after flow diversion in the treatment of middle cerebral artery bifurcation aneurysms.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The use of MRP examination findings (especially prolonged MTT ratio) may be beneficial in the prevention of ischemic complications, especially in patients who underwent FD stent treatment and in whom antithrombotic medication is planned to be completely discontinued.

INTRODUCTION

Flow diverter (FD) devices have been developed for secondary occlusion of intracranial aneurysms to provide vascular remodeling without aiming to fill the aneurysmal sac. The use of these devices has gained increasing acceptance over the last decade in the light of numerous studies demonstrating the safety and effectiveness of the flow diversion technique.[1–4] While almost all of the treatments were performed for aneurysms located at the level of the internal carotid artery (ICA) and within the circle of Willis in the early periods of this endovascular technique, technological advances have led to a substantial increase in treatment indications, including distally located aneurysms.[5–7]

The middle cerebral artery (MCA) is the second most common site for intracranial aneurysms after the anterior communicating artery, with most MCA aneurysms being located at the M1 division point.[8] Although there is no clear consensus on the first-line treatment option for MCA bifurcation aneurysms, there is increasing evidence for the efficacy and safety of flow diversion treatment of these aneurysms.[9 10]

One of the major concerns in patients undergoing flow diversion treatment is potential side branch occlusion, which may occur due to coverage of adjacent perforator and cortical branches by the FD device. In the published literature it has been revealed that different jailed arteries such as the ophthalmic, anterior choroidal, posterior communicating arteries, and MCA branches maintain their patency in most cases and most of the patients are usually asymptomatic.[11–13] Conversely, a recent meta-analysis reported occlusion in nearly 10% of jailed arteries during follow-up and found that ischemic symptoms related to MCA branch occlusion was 2.7%.[14] Therefore, revealing flow alterations in jailed arterial branches after flow diversion may be beneficial in predicting potential ischemic complications.[15] However, there are no long-term data from magnetic resonance perfusion (MRP) studies regarding jailed branches.

In this study we aimed to reveal MRP findings in conjunction with digital subtraction angiography (DSA) examination findings in patients with jailed MCA cortical branches during long-term follow-up after flow diversion. In addition, we also aimed to share treatment outcomes, clinical findings, and posttreatment magnetic resonance imaging (MRI) changes in cases with MCA bifurcation aneurysms treated with FD stents.

METHODS

Study population

This retrospective study was approved by our institutional ethics committee and carried out according to the requirements of the Declaration of Helsinki. All patients gave written informed consent to angiographic procedures, perfusion imaging, and the use of imaging data.

Eighteen patients, who underwent FD stent treatment for MCA M1, MCA bifurcation, and proximal M2 aneurysms (20 aneurysms in total) with a resulting jailed cortical branch and/or lateral lenticulostriate artery in our institution between 2014 and 2021 and who underwent control MRP studies at least 6 months postoperatively, were included in this study. Patients with a history of bilateral FD stent treatment on MCA, significant stenosis (≥50%) in the common carotid artery (CCA) and/or ICA and/or MCA, previous stroke, arteriovenous malformation/fistula, cranial surgical intervention, or cranial mass lesion related to the MCA territory were excluded from the study due to the fact that these conditions may cause misinterpretations in perfusion studies.

Indications of flow diversion

All treatment indications were discussed among neurosurgeons and neuroradiologists in a multidisciplinary neurovascular board. Wide-necked (>4 mm) aneurysms, giant aneurysms with partial thrombus or mass effect, dissecting aneurysms, and small aneurysms that are seldom treatable with surgery or conventional endovascular techniques were the main indications for FD stent treatment in this study group.

Preprocedural and Postprocedural medication

Clopidogrel (75 mg) and aspirin (100 mg) were administered orally for at least 5 days before the procedure. If not received before, the treatment was given orally in the form of a loading dose of 300 mg clopidogrel and 300 mg aspirin on the day of the procedure. Platelet function inhibition in the patients was confirmed by the collagen ADP resistivity test; patients with a platelet inhibition rate between 40% and 70% were treated with a FD stent. However, for patients whose platelet inhibition rate failed to reach 40% the aspirin dose was increased to 300 mg/day. In patients who still failed to maintain the appropriate platelet inhibition rate, in addition to 300 mg/day aspirin, the clopidogrel dose was doubled (150 mg/day) or dual-antiplatelet therapy was changed to mono-antiplatelet medication with 10 mg prasugrel (loading dose of 40 mg) or 2 × 90 mg ticagrelor daily. Endovascular treatment was performed in all patients after inducing general anesthesia and applying systemic heparinization. Following the placement of the femoral sheath, 5000 IU heparin was administered as an intravenous bolus and then as a continuous intravenous perfusion to maintain a 2–2.5-fold baseline activated clotting time (ACT) during the procedure.

After the procedure, unfractionated heparinization was extended to 24 hours in all patients, and low molecular weight heparin (LMWH) was administered for the next 3–5 days. Also, after discharge, it was recommended that patients take 75 mg clopidogrel/day for at least 6 months and 100 mg/day aspirin permanently, or in cases of clopidogrel non-response 10 mg prasugrel or 2 × 90 mg ticagrelor/day for 6 months and 100 mg/day aspirin thereafter. In cases in which total aneurysm occlusion could not be achieved, clopidogrel was discontinued after the sixth month and the aspirin dose was reduced to 100 mg.

FD stent technique

All FD stent implantations were performed by at least two senior neuroradiologists (CI, NK, and OK) using Philips Integris Allura and Allura Xper FD 20/20 Biplane Angiography (Philips Medical Systems, Best, The Netherlands). Unilateral femoral access was employed under general anesthesia in all patients. In the next step, a long introducer 6F sheath was navigated into the CCA and a distal access catheter into the ICA. To prevent vasospasm during the long sheath and distal access catheter navigation, 1 mL of 0.2 mg nimodipine was diluted to 10 mL with serum saline and injected slowly through a distal access catheter over an extended period of time (3–5 min).

After obtaining the appropriate study projection for the aneurysm that was to be treated, the compatible microcatheter-microguidewire system with the FD stent system was maneuvered beyond the aneurysm neck and the FD stent was unsheathed and deployed to cover the aneurysm neck under roadmap guidance. In all cases stent apposition to the vessel wall was scanned with flat-panel detector C-arm computed tomography angiography (FCTA) (Allura Xper FD 20/20; Philips Healthcare, Best, The Netherlands) in the neuroangiography suite in addition to regular angiographic images. When necessary, balloon angioplasty was performed to ensure a satisfactory stent apposition to the vessel wall. All patients underwent control angiography in anteroposterior, lateral, and working positions, and the procedure was terminated.

Posttreatment follow-up

Vascular closure devices were used for groin punctures in eligible patients. The patients were then transferred to the neurological intensive care unit and closely monitored for fluid balance, blood pressure, and neurological status.

At our institution, a standard follow-up protocol was used for the patient group: (i) at the first month, neurological examination and FDCTA; (ii) at the sixth month, DSA; (iii), at the twelfth month, neurological examination and FDCTA; and (iv) at the fifth year, DSA were performed. Starting from 2020, MRP was included in the protocol for patients who had a jailed cortical branch after flow diversion therapy and who had completed their sixth postoperative month. The results were evaluated by at least two senior neuroradiologists. The cases in which total aneurysm occlusion was detected 1 year after treatment were

followed up by annual clinical examination and, depending on the findings, appropriate radiological examinations (DSA, MRI, magnetic resonance angiography (MRA), computed tomography (CT), or FDCTA) were performed when necessary. If the aneurysm was still not completely occluded after 1 year, annual MRA was performed. Control DSA was planned in all patients at the fifth year after flow diversion treatment.

Treatment results were evaluated using DSA examination findings and graded according to the novel classification described by Cekirge and Saatci and created by expanding and adapting the impact of flow modification on the widely used Raymond–Roy Occlusion Classification (RROC) scale.[16] Morbidity was defined as a modified Rankin Scale (mRS) of >1. When the preoperative mRS was >1, morbidity was defined by any increase in the mRS score.

MRP imaging and image analysis

MRI scans were performed using a 3 Tesla MR scanner (Ingenia; Philips Healthcare). The MRI protocol included gradient recalled echo, time of flight (TOF) MRA, axial T2 weighted, axial fluid-attenuated inversion recovery (FLAIR), and diffusion weighted imaging (DWI). Dynamic susceptibility contrast (DSC) images were acquired using a gradient-echo echoplanar imaging sequence with the following parameters: repetition time (TR), 2011 ms; time-to-echo (TE), 40 ms; field of view (FOV), 224 × 224 mm; matrix size 96 × 94 mm; flip angle, 75°; voxel size, 2.33 × 2.33 × 4 mm; reconstructed voxel size, 1.75 × 1.75 × 4 mm). During dynamic acquisition a single dose of 0.1 mmol/kg intravenous gadobutrol (Gadovist; Bayer Schering Pharma, Berlin, Germany) was injected at a rate of 5 mL/s.

DSC MRP images with relative cerebral blood flow (rCBF), relative cerebral blood volume (rCBV), mean transmit time (MTT), and time-to-peak (TTP) maps were generated using a commercially available software package. All rCBF, rCBV, MTT, and TTP values were measured using similar areas of region of interest (ROI) on each DSC perfusion map for the levels of the MCA territory regarding the relevant jailed cortical branches. The measurements obtained with perfusion imaging were compared with the same level of contralateral MCA territory.

Statistics

All statistics were computed with SPSS 23.0 software. After the research data were digitized, frequency and percentage values were calculated for categorical variables and mean, median, and standard deviation values were calculated for continuous variables. Analyses were performed using Student's t-test, one-way ANOVA, and Pearson correlation tests following data properties. A value of $P<0.05$ was accepted as the limit of significance for all analyses and absolute P values were given for each analysis.

RESULTS

Eighteen patients treated with FD stents for a total of 20 MCA aneurysms with resulting jailed cortical branches or perforating arteries who underwent MRP studies were included in the study. Of these patients, 11 (61.1%) were female and 7 (38.9%) were male. Mean age was 48.83±12.76 years (range 19–66 years). Two (11.1%) patients had previously been treated endovascularly by coiling (n=1, 5.5%) and FD stent (n=1, 5.5%). Regrowth was demonstrated in follow-up DSA examinations in the aneurysm that had been treated by coiling. In the other case, the FD stent shortened at the distal end and the FD was shown to fall into the aneurysmal sac at follow-up in the third postoperative month, therefore a second FD stent was deployed telescopically. The mean diameter of aneurysms previously treated endovascularly was found to be 5.25±1.77 mm. There was no previous treatment history in 16 (88.9%) patients and the mean diameter of these aneurysms was 7.89±4.23 mm.

Except for 2 (11.1%) patients in whom two FD stents were placed telescopically to provide better coverage for the entire aneurysm neck, only one FD was deployed. Of the 20 total FD stents used, 11 were the flow redirection endoluminal device FRED/FRED Jr (MicroVention, Tustin, CA, USA) and 9 were the Pipeline Embolization Device, Pipeline/Pipeline Flex/Pipeline Flex Shield/Pipeline Vantage (Medtronic Neurovascular, Irvine, CA, USA). Successful stent deployment was achieved technically in all procedures. No additional coiling was used in treatment sessions. Patients' aneurysm characteristics are given in table 1.

Fourteen (78%) patients whose Clopidogrel resistance test (CRT) was found to be suitable under clopidogrel 75 mg and aspirin 300 mg underwent endovascular therapy and dual antithrombotic therapy was continued for 6 months following FD stent treatment. Four patients whose CRT test was not suitable following oral administration of clopidogrel 75 mg and aspirin 300 mg for at least 5 days were administered mono-antiplatelet therapy (2 patients with prasugrel 10 mg/day, 2 patients with ticagrelor 2 × 90 mg/day). All patients were followed up with oral 100 mg aspirin 6 months postoperatively following flow diversion.

The length of the total follow-up period ranged from 7 to 95 months (median 35 months). While complete occlusion was observed in 13 (65%) aneurysms, partial occlusion was achieved in 6 (30%) aneurysms. In 1 (5%) aneurysm, no dimensional change was observed despite FD stent treatment. In the follow-up DSA examinations, aneurysms treated with flow diversion were categorized as Class 1B in 8 (40%) aneurysms, Class 3 in 7 (35%) aneurysms, Class 1A in 3 (15%) aneurysms, Class 1C in 1 (5%) aneurysm, and Class 5 in 1 (5%) aneurysm, respectively, using the classification proposed by Cekirge and Saatci.[16]

All the aneurysms included in the study were related to a MCA bifurcation, and five aneurysms had MCA branches originating from the aneurysm dome. The total occlusion rate in these five aneurysms was 40% (n=2), whereas the total occlusion rate was found to be 67% (n=11) in the 15 aneurysms that were related to MCA branches with aneurysm neck origin. The mean age of patients with incomplete aneurysmal occlusion was 51.42 years compared with 47.18 years for patients with complete aneurysmal occlusion.

At least one of the bifurcation branches were covered ('jailed') by FDs in all patients. All the FD stents were deployed from the proximal MCA M2 segment to the MCA M1 segment except in one patient where the FD extended from the MCA M2 segment to the supraclinoid ICA; however, the dominant lateral lenticulostriate artery, which was most clearly selected portion of the lateral lenticulostriate artery in DSA, was jailed in 6 (33.3%) patients. Asymptomatic lacunar infarcts were detected in 2 (11.1%) patients in control MRI examinations. Moreover, no perforator branch occlusion was encountered in the follow-up DSA.

Of the total 18 patients, the superior trunk was jailed in 9 (50%) patients, whereas the inferior trunk was jailed in 9 (50%) patients. No symptomatic periprocedural complications were observed in the study group. In 1 (5.6%) patient a jailed cortical branch was found to be occluded in control angiograms at the follow-up performed 5 years after flow diversion. Nine 'jailed' cortical branches were shown to be patent with decreased caliber in control angiograms (50%), whereas eight cortical branches (44.4%) remained unchanged. Total aneurysmal occlusion was

Table 1 Patient characteristics

Patient	Aneurysms (n)	Aneurysm location	Aneurysm size (mm)	Flow diverter	Covered cortical branches and perforating arteries
1	1	Left MCA bifurcation	10×9	FRED JR 3×27–21 mm	Anterior temporal artery, MCA inferior division, lateral lenticulostriate arteries
2	1	Left MCA bifurcation	4×3	FRED JR 3×27–21 mm	MCA inferior division, lenticulostriate arteries
3	1	Right MCA bifurcation	5×3	FRED JR 2.5×18–13 mm	MCA superior division
4	1	Left MCA bifurcation	13×8	FRED JR 2.5×18–13 mm	MCA superior division, lenticulostriate arteries
5	1	Left MCA bifurcation	6×4	PED FLEX 2.75×16 mm	MCA superior division, lenticulostriate arteries
6	1	Right MCA bifurcation	12×10	FRED 3.5×22–16 mm	MCA inferior division
7	1	Left MCA bifurcation	7×6	FRED 3.5×22–16 mm	ACA A1 segment, MCA superior division, lateral lenticulostriate arteries
8	1	Right MCA bifurcation	7×6	PED 3×14 mm	MCA inferior division
9	3	Right MCA bifurcation	12×7	PED 3×16 mm	MCA superior division
10	1	Right MCA M1	6×3	PED 2.75×16 mm	MCA inferior division
11	1	Left MCA M1-M2 dissecting	20×12	Telescopic PED 3×20 mm, PED 3×18 mm	MCA superior division
12	1	Right MCA bifurcation	5×4	FRED 3×19–14 mm	MCA superior division
13	1	Right MCA bifurcation	5×4	FRED 3×19–14 mm	MCA superior division
14	1	Left MCA bifurcation	9×6	FRED JR 3×19–14 mm	MCA inferior division
15	1	Right MCA bifurcation	6.5×6	Telescopic FRED JR 2.5×18–13 mm, FRED JR 2.5×18–13 mm	MCA inferior division
16	1	Right MCA bifurcation	7×5	PED 3×20 mm	MCA inferior division
17	1	Right MCA bifurcation	5×3	PED Vantage 3×14 mm	MCA superior division, lateral lenticulostriate arteries
18	1	Left MCA bifurcation	7×5	PED Vantage 2.75×20 mm	MCA inferior division

ACA, anterior cerebral artery; FRED, flow redirection endoluminal device; MCA, middle cerebral artery; PED, Pipeline Embolization Device.

detected in 10 of 12 (83.3%) aneurysms in patients with decreased caliber or occlusion in the jailed branch after flow diversion treatment. The patients whose jailed branches were found to be occluded or reduced in caliber were asymptomatic except for 1 (10%) patient in the follow-up. The total aneurysmal occlusion was detected in 3 (37.5%) aneurysms in cases whose jailed branches remained unchanged in caliber, while decreased a sac diameter was observed in 4 (50%) aneurysms in these patients. A minor infarct occurred at the ninth postoperative month in the MCA territory of a patient who was recommended to use aspirin 100 mg but who was not taking the antithrombotic medication regularly. The mRS score of the patient was 1 after 3 months following a minor stroke. The mRS scores of the other patients were evaluated as 0 during the neurologic follow-up examinations. During the follow-up period, no hemorrhagic complications, permanent morbidity, or deaths occurred.

The time-span from flow diversion to MRP examination ranged from 6 months to 63 months, with a median time of 31 months. In the MRP it was remarkable that the MTT, TTP, and rCBF values of the patients showed statistically significant differences compared with the contralateral side ($P<0.05$). However, there was no statistically significant change in rCBV values when compared with the same level of the contralateral MCA territory (figures 1 and 2). The mean MTT prolongation was found to be 1.34 s (± 0.70 s, range 0.06–2.72 s) compared with the contralateral side in the MCA territory supplied by the cortical MCA branches jailed by flow diversion. The mean MTT ratio of 18 cases with jailed cortical branches was found to be 1.20 (± 0.14, range 1.01–1.65).

The mean TTP ratio of 18 cases with jailed cortical branches was found to be 1.06 (± 0.39, range 1.01–1.14). The mean TTP prolongation was found to be 1.18 s (± 0.63 s, range 0.23–2.42 s) compared with the contralateral side in the MCA territory supplied by the cortical MCA branches jailed by flow diversion. There was no statistically significant difference in the mean MTT prolongation, MTT ratio, rCBF reduction, and TTP prolongation values obtained from the MCA territories between the cases with occluded branch or reduced branch calibration and the cases without reduced caliber in covered cortical branches after jailing with FDs ($P>0.05$). The quantitative MRP findings are given in tables 2 and 3.

In ANOVA tests no statistically significant difference was found between the MTT ratio (1.22 vs 1.17; $F=0.652$; $P=0.431$), MTT prolongation (1.50 vs 1.15; $F=1.132$; $P=0.303$), TTP ratio (1.07 vs 1.06; $F=0.093$; $P=0.764$), TTP prolongation (1.27 vs 1.07; $F=0.237$; $P=0.663$), rCBV changes (6% vs −0.5%; $F=0.545$; $P=0.471$), rCBF changes (–12.4% vs −15.25%; $F=0.170$; $P=0.686$) for dual mesh-layer (Flow Re-Direction Endoluminal Devices) and single-layer (Pipeline Embolization Devices) flow diverters.

DISCUSSION

The use and indications of FD stents in the treatment of intracranial aneurysms are gradually increasing. There are several studies and case reports showing that cerebral perfusion changes may occur in the early period after FD stent deployment.[17 18] However, no long-term perfusion study has been performed with accompanying DSA examination findings regarding the territories fed by cortical branches jailed after MCA aneurysm treatment with flow diversion. The primary goal of this study was to investigate and reveal MRP findings in conjunction with DSA examination findings in patients with jailed MCA cortical branches during long-term follow-up after flow diversion. We also aimed to share the long-term clinical and angiographic follow-up results regarding flow-diversion treatment of complex MCA aneurysms.

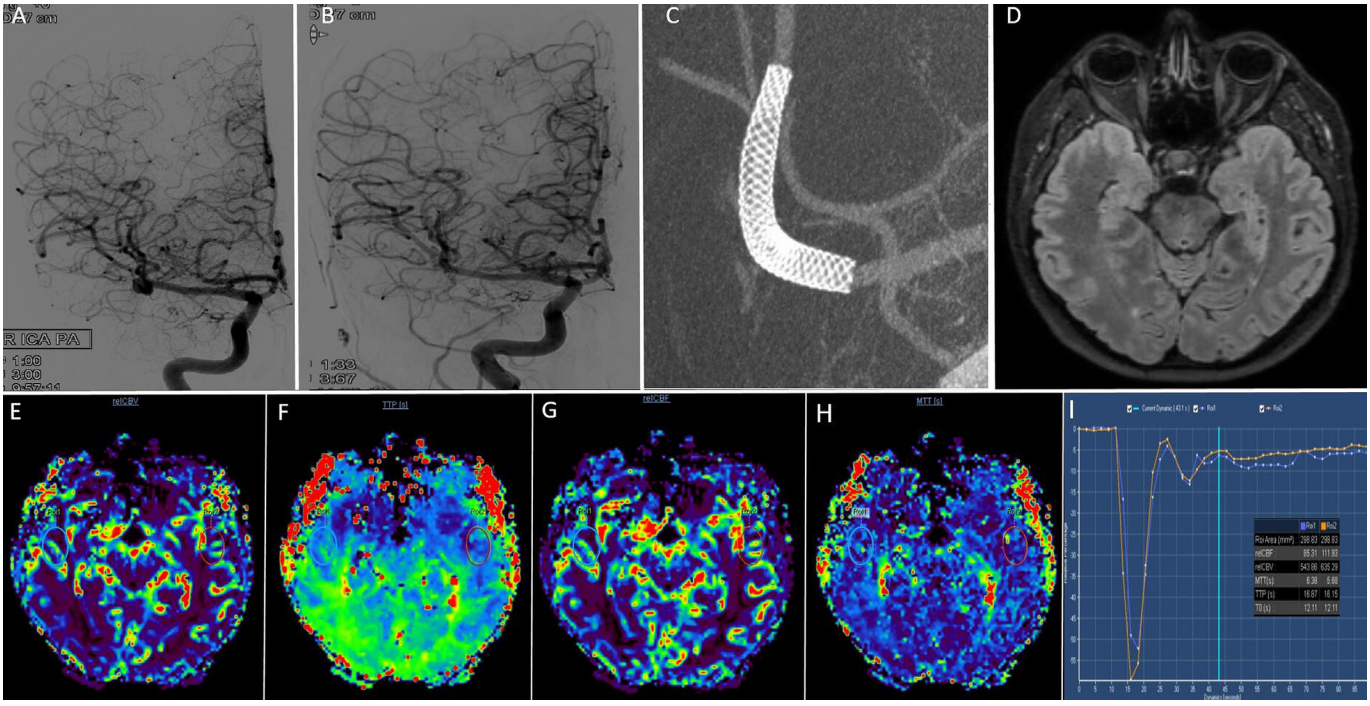

Figure 1 Patient 16. Digital subtraction angiography (DSA) with anterior–posterior view (A) showing a saccular aneurysm of the right middle cerebral artery (MCA) bifurcation. Five-year follow-up DSA with anterior–posterior view (B) and flat detector computed tomography angiography (FDCTA) image (C) demonstrating the complete occlusion of the aneurysm with the luminal patency of the stent, which extends from the MCA M1 segment to the proximal MCA M2 segment superior trunk. Axial fluid-attenuated inversion recovery (FLAIR) image (D) revealing the absence of any ischemic lesion related to the territory associated with the MCA inferior trunk that was jailed following flow diversion. Relative cerebral blood volume (rCBV) (E), relative cerebral blood flow (rCBF) (F), mean transit time (MTT) (G), time-to-peak (TTP) (H) maps and measurement results (I) are shown on dynamic susceptibility contrast (DSC) magnetic resonance perfusion images. An increase in TTP and MTT and a decrease in rCBF are observed in the jailed right MCA inferior trunk territory.

A previous study conducted to reveal the results regarding the covered cortical branches and perforating arteries related to flow diversion for MCA aneurysms stated that all branch occlusions were asymptomatic, as the supply of their cortical territories was taken over by leptomeningeal collaterals in all cases.[19] Another study revealed that a branch is kept patent whenever there is a flow demand through it in the absence of rich distal collateral flow.[20] In our case series, a symptomatic ischemic event was observed in only 1 (5.9%) patient, confirming previously published studies indicating that covered branches in cases treated with flow diversion were clinically well tolerated.[19–21] However, contrary to our study, there are other published studies in which the rate of postprocedural permanent morbidity exceeds 20% of patients with an mRS score of >1 at the last follow-up.[9 22]

Complete aneurysmal occlusion rates (90%) were found to be higher in cases with reduced caliber or occlusion of the jailed cortical branch in our study, similar to an experimental and also a previous clinical study.[23 24] Conversely, in the study conducted by Iosif *et al* no correlation was found between cortical branch occlusion and aneurysmal sac occlusion, which is in contrast to our findings.[10] Asymptomatic lacunar infarcts were detected in 2 (11.1%) patients in control MRI examinations during the follow-up period in our study group; however, a previously reported series revealed clinically asymptomatic new lacunar infarct findings in up to 29% of the patients in the follow-up MRI examination.[18]

The factors causing incomplete aneurysm occlusion after FD stent treatment is also a current research topic. The study by Hanel *et al* demonstrated that the patients with older age and the aneurysms related with the involvement of side branch may be associated with higher rates of incomplete aneurysm occlusion following flow diversion .[25] The mean age of patients in our study group with incomplete aneurysmal occlusion was 51.42 years compared with 47.18 years for patients with complete aneurysmal occlusion. Moreover, the total occlusion rate was found to be lower (40%) in aneurysms with an MCA branch originating from the aneurysm dome compared with aneurysms with an MCA branch originating from the aneurysm neck (67%).

In perfusion–diffusion mismatch tissue, prolonged MTT (>5 s) and very low rCBF (≤6 mL/100 mL/min) are associated with a high risk of infarction that is largely independent of recanalization status.[26] Statistically significant changes in MTT, TTP, and rCBV values in MRP measurements obtained from our study group were remarkable. In the present study, 1.36 s mean MTT prolongation, 1.19 s mean TTP prolongation, and approximately 14% mean rCBF decrease in the MCA territory supplied by cortical MCA branches covered following FD stent deployment compared with the contralateral side were detected, and these values are relatively moderate compared with the perfusion findings in acute stroke. The reason for the rare ischemic findings in the territory fed by the jailed branch was suggested to be because the supply of their cortical territories had been taken over by leptomeningeal collaterals.[19]

In a study conducted by Grubb *et al* to determine whether increased positron emission tomography (PET) MTT ratio calculated using mean ipsilateral to contralateral measurements in the MCA territories was associated with an increased risk of ipsilateral stroke it was discovered that the patients with an MTT cut-off ratio of 1.387 or higher had a 29.3% 2-year risk of ipsilateral stroke compared with 4.6% for the patients with a PET MTT ratio below the cut-off value (P<0.001).[27] In our study the mean MTT ratio of the 18 patients with jailed cortical branch was estimated to be

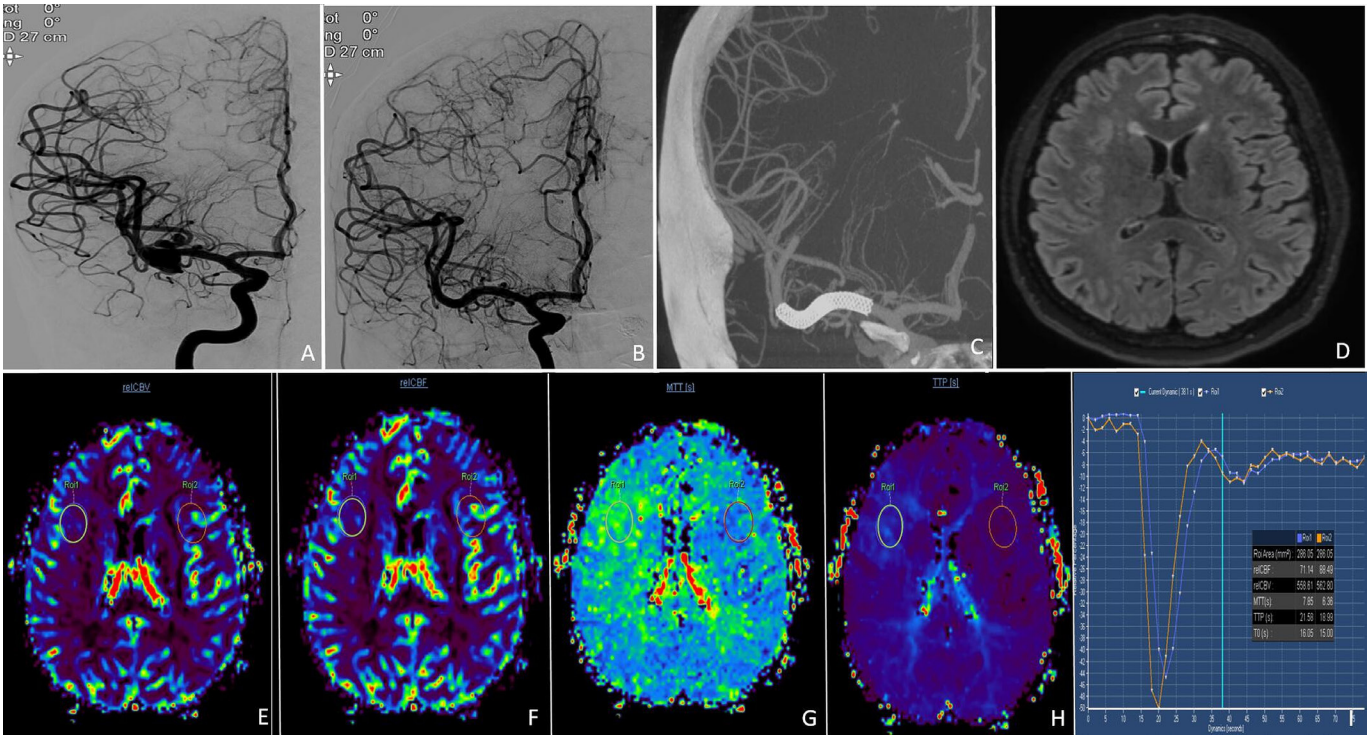

Figure 2 Patient 9. Digital subtraction angiography (DSA) with anterior–posterior view (A) showing a trilobulated aneurysm of the right middle cerebral artery (MCA) bifurcation. Two-year follow-up DSA with anterior–posterior view (B) and flat detector computed tomography angiography (FDCTA) image (C) demonstrating the complete occlusion of the aneurysm with the luminal patency of the stent, which extends from the MCA M1 segment to the proximal MCA M2 segment inferior trunk. The MCA superior trunk (white arrow) is shown to be slightly reduced in caliber on DSA with an anterior–posterior view (B). Axial fluid-attenuated inversion recovery (FLAIR) image (D) revealing the absence of any ischemic lesion related to the territory associated with the MCA superior trunk that is jailed after flow diverter stent treatment. Relative cerebral blood volume (rCBV) (E), relative cerebral blood flow (rCBF) (F), mean transit time (MTT) (G), time-to-peak (TTP) (H) maps and measurement results (I) are shown on dynamic susceptibility contrast (DSC) magnetic resonance perfusion images. An increase in TTP and MTT and a decrease in rCBF are observed in the jailed right MCA superior trunk territory.

1.2047, and the MTT ratio was found to be higher than 1.387 in only one case. This case was a patient who had a history of irregular antithrombotic medication use and had experienced a minor stroke in the ninth postoperative month. In the literature, clinically significant thromboembolic events were observed in patients, similar to the case that had a symptomatic ischemic event in our series, who discontinued antiplatelet therapy against medical advice. As a result of reverting to antiplatelet therapy rapidly following the ischemic event, the long-term follow-up mRS scores of these patients were found to be ≤1.[20 21] In the light of experience gained from previously published cases and the present study, complete discontinuation of antithrombotic medication may increase the risk of stroke in patients with jailed cortical branches following flow diversion, especially in cases with significantly prolonged MTT values obtained from the MRP examination. Therefore, care should be taken if antiplatelet therapy is planned to be completely discontinued in cases with resulting jailed cortical branches following flow diversion in the treatment of MCA aneurysms, and MRP findings should be used.

LIMITATIONS

Our study has several limitations. First, our study was carried out in a limited number of patients and it had a retrospective design. Second, although the same ROI sizes were used in the MRP examinations, alterations in ROI location in the measured MCA territory could create minor changes in the quantitative perfusion values. However, these changes were not at a level that would affect the results proportionally and qualitatively. In addition, the diversity of the stents used in the study and the heterogeneity in the postoperative

Table 2 Comparison of magnetic resonace perfusion parameters in the middle cerebral artery territory fed by the jailed cortical branch with those on the contralateral side

Parameter	MCA territory supplied by jailed branch	Contralateral side	T	P value
MTT (s)	8.49±1.47	7.15±1.28	8.141	<0.001*
rCBV (mL/100 mg)	490.86±231.08	467.07±195.48	1.191	0.250
rCBF (mL/100 mL/min)	56.36±22.55	64.62±22.35	−3.898	0.001*
TTP (s)	20.37±2.70	19.19±2.77	7.936	<0.001*

*P value <0.05 is statistically significant.
MTT, mean transit time; rCBF, relative cerebral blood flow; rCBV, relative cerebral blood volume; TTP, time-to-peak.

Table 3 Comparison of magnetic resonance perfusion parameters between groups with and without reduced calibration in the jailed cortical branch at follow-up after flow diversion treatment

Parameter	Reduced caliber/occluded cortical branch (n=10)	No change in calibration (n=8)	P value	F
MTT prolongation (s)	1.56±0.69	1.08±0.65	0.15	2.267
MTT ratio	1.24±0.16	1.15±0.10	0.18	1.930
Mean CBF decrease (%)	13.01	14.30	0.85	0.035
TTP prolongation (s)	1.37±0.52	0.93±0.70	0.14	2.332
TTP ratio	1.07±0.3	1.05±0.4	0.16	2.142

P value <0.05 is statistically significant.
CBF, cerebral blood flow; MTT, mean transit time; TTP, time-to-peak.

acquisition periods of the MRP examinations, although the latter were all performed after the sixth month, are other limitations.

CONCLUSIONS

Our study shows that flow diversion treatment of complex bifurcation aneurysms can be effective and safe with a low risk of permanent morbidity and mortality. A statistically significant delay, especially in the MTT and TTP values on MRP examination, was detected in the territory vascularized via a jailed arterial branch following flow diversion when compared with the contralateral MCA territory, and these changes in arterial flow were rarely accompanied by clinical findings. Evaluation of MRP findings may be meaningful, especially in cases where antiplatelet therapy is to be completely discontinued. It is clear that large-scale and multicenter studies are required in order to clarify the complex flow changes following flow diversion.

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ORCID iDs
Bora Korkmazer http://orcid.org/0000-0001-7015-365X
Ahmet Kursat Karaman http://orcid.org/0000-0002-4870-0597
Civan Islak http://orcid.org/0000-0002-3626-6244

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