



# Microsurgical management of complex middle cerebral artery aneurysms

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## Abstract

**Introduction:** Management of complex aneurysms of the middle cerebral artery (MCA) is challenging and requires individualized treatment strategies. Our review aimed to analyze experience with the treatment of complex MCA aneurysms using revascularization and artery sacrifice techniques.

**Methods:** We have reviewed 9 original articles on patients' treatment with complex MCA aneurysms. Depending on the localization of the complex aneurysms of MCA, various methods of parent artery sacrifice, revascularization strategies, surgical results, outcomes, and complications were reviewed.

**Results:** We have analyzed the treatment of 244 patients with 246 complex MCA aneurysms in 9 different groups. From 67 to 100% of cases, the aneurysms were occluded successfully. Bypass patency resulting from the performed revascularization methods was from 83.3 to 100%. The main complications included ischemic disorders related to occlusion of the bypass graft or perforators injury. Morbidity in some reviews varied from 2.4 to 6.9%. The majority of patients in late follow-up showed good outcomes 0-2 on the modified Rankin scale and 4-5 on Glasgow Outcome Scale. Illustrative clinical cases of the patients with complex MCA aneurysms treated at the Federal Neurosurgical Center were presented.

**Conclusion:** Complex aneurysms of the MCA are very challenging lesions. The surgical strategy for treating complex MCA aneurysm should take into account vascular anatomy, complex morphology, its localization, and rupture status of each case.

**Keywords:** giant aneurysm; complex aneurysm; middle cerebral artery; bypass surgery

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## Introduction

Regardless of their localization, treatment of complex intracranial aneurysms (CIAs), especially for complex middle cerebral artery (MCA) aneurysms, requires special skills and knowledge in vascular neurosurgery and presents a great challenge even for an experienced surgeon. The pathology includes aneurysms larger than 2.5 cm; aneurysms involving perforating vessels (lenticulostriate arteries or LSA) or efferent arteries; previously endovascularly or surgically treated aneurysms; aneurysms of complex shape (fusiform, serpentine or dolichoectatic); mycotic or infected aneurysms; dissected aneurysms; aneurysms with a wide or absent well-defined neck; thrombosed aneurysms; aneurysms with atherosclerotic or calcified walls and neck lesions. The angioanatomical features of the MCA are additional challenge for complex aneurysms surgery. Complex MCA aneurysm surgery is often not limited to simple clipping or clip reconstruction of the aneurysm's neck but may demand a more complex procedure to occlude the aneurysm.

The variety of approaches for surgical treatment of complex MCA aneurysms and a large number of different revascularization techniques is dictated not only by the aneurysms' anatomical features but also by their localization that explains the lack of unified treatment strategies.

## Materials and methods

To analyze the features of surgical treatment and the results of surgery in patients with complex MCA aneurysms, 9 original papers were reviewed (Table 1). The papers concerning CIAs of other localizations, as well as those describing single cases, were excluded. In total, the surgical treatment of 244 patients with 246 complex MCA aneurysms was analyzed. Such treatment features as surgical treatment algorithms, methods of blood flow shutdown; revascularization techniques; vascular graft types; and patient outcomes and complications were considered.

**Table 1.** Treatment of patients with complex MCA aneurysms of different localizations.

Authors, Year	Patients	Aneurysm localization				Aneurysm occlusion technique						Bypass type			Graft type	Periop. control	Postop. control
		M1	Bif.	Distal	DC	RC	PO	DO	Tr/Res	ICA sacrifice	Coiling	EC-IC	IC-IC	Comb.			
Zhu et al., 2013	58	7	28	24	8	25			25	1		17	5		RAG	ICG-VA, Doppler, SEP/MEP	CTA, MRI, DSA
Wessels et al., 2019	50	5	30	15			19	10	21			31		18	RAG, SVG	ICG-VA, Doppler	MRI, CTA, DSA
Natarajan et al., 2019	42	12 <sup>1</sup>	20	11	5	20	4	1	16			28	24		RAG, SVG	ICG-VA, Doppler	DSA
Meybodi et al., 2017	30	8	5	17			8	1	21			12	13	5	RAG, SVG	SEP, MEP - monitoring	Angiography
Kivipelto et al., 2014	24	7	8	9	4		6 <sup>2</sup>	8	6			21	4		SVG	ICG-VA, DSA, ultrasonic flow probe	CTA, DSA
Kalani at al., 2012	16	5	2	9			8 <sup>3</sup>	4	1			16			RAG, SVG	Catheter angiography, ICG-VA	Angiography
Wang et al., 2018	12	5	6	1			8		4			12			RAG	ICG-VA, Doppler	CTA
Lee et al., 2018	6		1	5	2				3		1	6			not applied	ICG-VA, Doppler	DSA
Ravina et al., 2019	6		4	2	1	3 <sup>4</sup>			2				6		not applied	ICG-VA	Angiography, CTA

**M1** - M1 segment; **Bif.** –M1-M2 bifurcation; **Dist** - distal segment; **DC** – direct clipping; **RC** – reconstructive clipping; **PO** – proximal occlusion; **DO** – distal occlusion; **Tr/Res** – trapping/resection; **EC-IC** - extra-intracranial bypass; **IC-IC** - intra-intracranial bypass; **Comb.** – combined revascularization.

Footnotes:

1. including 3 anterior temporal artery bifurcation;
2. 1 endovascular proximal occlusion;
3. aneurysm occlusion include 2 spontaneous thrombosis and 1 aneurysm wrapping/proximal endovascular occlusion;
4. microsurgical strategy include 2 proximal clip occlusion and 1 aneurysm trapping.

## Classification of complex MCA aneurysms

The pathology includes aneurysms larger than 2.5 cm; aneurysms involving perforating vessels (lenticulostriate arteries or LSA) or efferent arteries; previously endovascularly or surgically treated aneurysms; aneurysms of complex shape (fusiform, serpentine or dolichoectatic); mycotic or infected aneurysms; dissected aneurysms; aneurysms with a wide or absent well-defined neck; thrombosed aneurysms; aneurysms with atherosclerotic or calcified walls and neck lesions<sup>1,2,3,4</sup>. The angioanatomical features of the middle cerebral artery (MCA) are an additional complication for complex MCA aneurysms surgery. For example, limited accessibility of the M1 and M2 branches often hidden behind the mass of a giant aneurysm, and LSA or efferent arteries involvement with the aneurysm's wall or bottom create high risks of ischemic complications<sup>4,5,6,7,8</sup>. Also, the MCA supplies the largest and most important areas of the cerebral hemispheres and, at the same time, does not have communicating vessels similar to those of the anterior and posterior cerebral arteries providing compensatory blood flow in case of main vascular trunk occlusion. Hence, blood flow disturbance in the MCA territory can lead to severe complications and gross neurological deficits<sup>2</sup>. Moreover, complex MCA aneurysm surgery is not often limited to simple clipping or clip reconstruction of the aneurysm's neck but requires more complex approaches to occlude the aneurysm using various revascularizing techniques. Depending on their localization, the complex MCA aneurysms were classified into those affecting the M1 segment (pre-bifurcation aneurysms); aneurysms of M1 bifurcation (bifurcation aneurysms); and more distal (M2-M4) aneurysms (post-bifurcation aneurysms)<sup>2,9</sup>. Zhu et al., 2013 identified three types of complex MCA aneurysms: M1 aneurysms (type A); bifurcation or M2 segment (type B); M3 and more distal segments (type C)<sup>4</sup>. Wessels et al., 2017 proposed a more complex classification of the pathology, including 6 subtypes such as fusiform/dysplastic M1 aneurysms without signs of parietal thrombosis (type 1a)<sup>8</sup>; those with parietal thrombosis (type 1b); bifurcation aneurysms domed upward (type 2a); those laterally domed (type 2b); those domed downward (type 2c); M2-M3 aneurysms with no bifurcation involved (type 3)<sup>8</sup>. The authors advocated various methods and algorithms for surgical treatment of the pathology based on the affected MCA segment summarized in Table 1.

## Surgery of complex MCA aneurysms

### M1 segment

The papers reviewed mark this segment as the hardest one. Complex M1 aneurysms accounted for about 20% of the pathologies treated (see Table 1). Different complex aneurysms might develop in this segment, with fusiform ones being the most frequent<sup>9</sup>. The absence of a neck, often detached and fragile walls, and presence of intraluminal thrombosis made both direct clipping and reconstructive clipping difficult, provoking many recanalizations, complications, and mortalities. Endovascular options in such cases were also limited<sup>9</sup>.

The M1 aneurysms in the considered series might involve the LSA or efferent vessels that further complicated their surgical treatment due to the high risk of circulatory disorders in the subcortical structures<sup>7,10</sup>. Approximately in 25% of the cases, the LSA originated from an aneurism<sup>2</sup>, which had to be taken into account when selecting a treatment strategy as well as the presence or absence of a rupture<sup>2</sup>.

LSA involvement (type Ia according to Wessels 2017<sup>8</sup>), made it impossible to perform direct clipping, clip reconstruction, or trapping due to the high risk of stroke in the subcortical structures. In such a situation, the optimal solution was either proximal or distal occlusion of blood vessels<sup>2,11,12</sup> followed by a bypass to maintain blood flow in the MCA territory<sup>6,7</sup>. In case of non-functioning LSA involvement due to either intimal dissection or the presence of parietal blood thrombus in aneurysm cavity (type Ib according to Wessels 2017<sup>8</sup>), one could perform trapping under electrophysiological monitoring to reduce the risk of subcortical stroke. Another option for both Ia and Ib types was performing a high-flow extra-intracranial anastomosis (EICA) to revascularize one of the M2 branches, perfuse the M1-M2 bifurcation and arrange retrograde flow to go through the aneurysm to the LSA<sup>8,10</sup>. The bypass technique included internal carotid artery/external carotid artery/common carotid artery (ICA / ECA / CCA) – MCA<sup>2,10</sup>, ICA / ECA / CCA – MCA<sup>2,10</sup>, maxillary artery (IMA) – MCA<sup>13</sup> with high-flow grafts from the radial artery (RA) or saphenous vein (SV).

As for low-flow anastomoses, according to Natarajan 2019, a superficial temporal artery (STA)-MCA bypass had low efficiency for revascularization of the M1 segment<sup>10</sup>. Nevertheless, it was previously shown that this anastomosis created blood flow up to 100 ml/min in the M1 segment, which is sufficient for supplying the entire MCA territory that requires no more than 50 ml/min<sup>9</sup>. An alternative option could be an STA-MCA bypass with radial artery graft (RAG) followed by aneurysm trapping<sup>4</sup>.

Direct or reconstructive clipping (clip reconstruction) was preferred as the simplest option when perforating vessels of the M1 segment were not involved with the aneurysm's wall, or bottom, direct or reconstructive clipping (clip reconstruction) was preferred as the simplest option. Also, coagulation could reduce the aneurysm in size and make it suitable for clipping<sup>4</sup>. These techniques minimized the risk of stroke<sup>4</sup>. More complex approaches were used if clip reconstruction was not applicable due to LSA absence. So, in the presence of a short area of pathology with the afferent and efferent vessels of sufficient tortuosity and length, trapping and resection could be performed, followed by end-to-end re-bypass formation<sup>2</sup>. If a more extended area was resected and there was a tension in the connected artery ends or a pathologically altered aneurysmal wall was retained, it was permissible to perform graft interposition. As for the grafting strategy, preference was given to RA grafts since they were an excellent match to the M1 segment in diameter.

Another alternative to re-bypass or interposition was EICA (low-flow or more often high-flow one)<sup>2</sup>, or IMA -MCA bypass with RAG<sup>3</sup>. It should be noted that STA-RAG-MCA bypass required a short interposition graft and no additional neck incision<sup>4</sup>.

### Bifurcation segment

Complex aneurysms of MCA bifurcation in the considered patient series required more complex revascularization techniques. Unlike the M1 aneurysms, they were often thrombosed, had a saccular structure<sup>14</sup> could reach larger sizes (if compared to the M1 aneurysms), and often had an impact/mass-effect on the surrounding structures<sup>9</sup>.

The bifurcation aneurysms were distinguished by the number of M2 branches involved (usually one or two) that could originate either from the wall or the bottom of the aneurysm. In the series analyzed, they accounted for up to 41% of all the complex MCA aneurysms considered.

To treat a bifurcation aneurysm, one could perform the traditional multi-clip reconstruction<sup>9</sup>, but this technique was not applicable in all the cases, and sometimes one had to resort to more complex surgical treatment options, which usually included direct clipping of the aneurysm and one M2 branch, revascularization and occlusion of the second M2 branch using various bypasses (either low – and high-flow EICA or intra-intracranial (IC-IC) bypass)<sup>4,10,15</sup>. If both M2 branches were involved, a side-to-side IC-IC bypass, in-situ bypass (M2-M2, M3-M3) with further proximal or distal occlusion<sup>7,9</sup> or trapping of the entire bifurcations with aneurysms (if no LSA involvement) could be performed<sup>4,15</sup>. Proximal occlusion was preferable in case of aneurysm rupture, distal occlusion – if the M1 segment was difficult to access for clipping or if it carried the LSA<sup>9</sup>. To avoid serious ischemic complications, all branches of the MCA bifurcation were revascularized<sup>10</sup>. The advantage of the IC-IC bypass over EICA was a relatively straightforward performance and good donor-recipient matching. The technique required creating only one bypass and needed no graft harvesting, avoiding harvesting-related complications. Besides, if compared to EICA, IC-IC bypass had higher postoperative patency<sup>15</sup>. If it was impossible to create an IC-IC bypass for revascularization of both M2 branches, high-flow EICA with a Y-grafting (RA or SV)<sup>10</sup>, or STA-RA-MCA, STA-MCA bypasses could be performed<sup>4</sup>.

### **Distal segments**

In the considered patient series, the aneurysms of distal localization accounted for about 39% of the complex MCA aneurysms. They were smaller in size and after their resection, small excisional spaces usually remained<sup>2</sup>. Distal MCA aneurysms were easier to revascularize<sup>10</sup>, which led to more tremendous surgical success if compared to the M1 aneurysms. The proximal and distal MCA segments were easily accessible by performing wide Sylvian fissure dissection. It is also important that perforating arteries were usually not found at this level<sup>8</sup>. If direct clipping of such an aneurysm was impossible, proximal or distal (in the absence of rupture), occlusion could be performed. Their relative accessibility also made trapping or resection possible<sup>8</sup>. The creation of a single or double-barrel STA-MCA bypass was the simplest method to revascularize the distal branches of the segment<sup>8</sup>. Since the M2-M3 segments were quite redundant and tortuous and had a sufficient length, their aneurysms could be easily resected using an end-to-end bypass (re-bypass), or by performing RAG or SVG interposition followed a side-to-side bypass, or by reimplantation to preserve blood flow in the distal MCA<sup>10</sup>. Equally, one could perform an in-situ IC-IC bypass (e.g., M3-M3)<sup>4,15</sup>.

Analysis of the various strategies for surgical treatment of MCA aneurysms in the considered patient series has demonstrated that high-flow EICA and proximal occlusion, as well as trapping and resection of the aneurysm, are the most common surgery of M1 MCA aneurysms as well as STA-MCA EICA with RAG is the most common bypass. Direct clipping or clip reconstruction followed by IC-IC or STA-MCA bypass are the optimal strategies for the treatment of MCA bifurcation aneurysms.

The method of choice in the surgery of distal MCA aneurysms is proximal occlusion and trapping/resection. STA-MCA bypass and IC-IC re-bypass are the most common revascularization options, unlike high-flow EICA that is not so commonly used. Interestingly, the most common occlusion techniques have been proximal occlusion, resection/trapping, and clip reconstruction. As for revascularization methods, STA-MCA bypass (including that with RAG) and high-flow EICA have been the most common.

The choice of occlusion and revascularization method has been determined by the surgeon's preference and CIA localization and angioanatomy, e.g. while Zhu et al., 2013 preferred clip reconstruction, trapping, or resection followed STA-MCA bypass with RAG for all the three MCA segments<sup>4</sup>, Wang et al., 2019 preferred to perform IMA bypass with RAG<sup>3</sup>, Kivipelto et al., 2014, Kalani et al., 2012 and Lee et al., 2018 relied on STA-MCA bypass to treat bifurcation, distal complex MCA aneurysms<sup>6,7,16</sup> and Ravina et al., 2019 mainly performed IC-IC bypasses<sup>15</sup>. High-flow EICA was used for revascularization, followed by proximal (more often) or distal occlusion or trapping of the complex aneurysms<sup>8</sup>.

### **Revascularization and bypass patency**

According to the authors, the main objective of revascularization in complex MCA aneurysms treatment was to provide blood flow in the distal segments of the MCA and maintain retrograde blood flow in the proximal segments without perfusion deficit in case it was impossible to clip the aneurysm or there was a high risk of ischemic disorders due to aneurysm occlusion<sup>1,7,9,17,18</sup>. The need for revascularization in the considered patient series varied between 1<sup>7,9</sup> and 2.1%<sup>2</sup>.

In the patient series reviewed, a total of 216 revascularization bypasses were performed. Among them, low-flow STA-MCA bypasses prevailed (35.5%), while high-flow ECA-MCA and intracranial bypasses were performed less frequently (24 and 24 %, respectively). Anastomoses with the maxillary artery comprised 5.5% of the total, and combined revascularization was performed in 6 % of the cases.

As a graft, RAs and SVs were used with the choice to be determined by blood supply requirements in the area to be occluded<sup>19</sup>, RAGs were chosen more often (see Table 1). To monitor bypass patency, intraoperative indocyanine green videoangiography (ICG-VA) /contact Dopplersonography and postoperative angiography were used (see Table 1). In general, in the late postoperative period, the bypasses had good patency (95% of patients had 83.3-100% patency rate, Table 2).

According to the authors, bypass surgery was a non-standard procedure and required careful preoperative planning for each patient<sup>9,20</sup>. The most important issues in the planning are determining the strategy of how to handle the aneurysm and choose the kind of revascularization<sup>21</sup>.

To date, despite numerous variants of revascularizing techniques have been proposed<sup>2,6,7,22</sup>, there is no general strategy for their application to treat complex MCA aneurysms. In general, high-flow anastomoses were chosen to revascularize large-diameter proximal arteries or multiple distal branches in the case of pre-bifurcation and bifurcation aneurysms, and low-flow anastomoses – for revascularization of small-diameter distal arteries<sup>2,20</sup> (**Table 3**).

**Table 2.** Complex MCA aneurysm treatment results: bypass patency, the efficiency of occlusion, and treatment outcomes.

Authors, Year	Patients, n	Patients with ruptured aneurysms, n	Aneurysms, n	Bypasses, n	Bypass occlusion, long-term period, n	Residual aneurysm, long-term period, n	Follow up, months (mean)	mRS			GOS		
								0-2	3-5	6	4-5	2-3	1
Zhu et al., 2013	58	27	59	22	1	11	38				52	3	4
Wessels et al., 2019	50	2	50	49	2	11	6	42	5	3			
Natarajan et al., 2019	42	13	43	52	1	0	39	36	5	1			
Meybodi et al., 2017	30	8	30	30	3	1	28	24	6	0			
Kivipelto et al., 2014	24	2	24	25	2	0	27	20	3	1			
Kalani et al., 2012	16	2	16	16	1	3	2	13	3	0			
Wang et al., 2018	12	3	12	12	2	0	53	12	0	0			
Lee et al., 2018	6	3	6	6	0	0	52	6	0	0			
Ravina et al., 2019	6	0	6	6	0	2	12	6	0	0			

**Table 3.** Different types of bypasses which are used in CIA treatment.

Type of bypass	Donor	Recipient	Flow type	Flow	Graft
Low-flow 1 barrel bypass	Superficial temporal artery, Occipital artery	M2, M3, M4, P2, PICA, AICA	Low-flow	Till 50 ml/min	-
Low-flow 2 barrel bypass	Superficial temporal artery, Occipital artery	M2, M3, M4, P2, PICA, AICA	Low-flow	Till 100 ml/min	-
Middle-flow bypass	Internal maxillary artery	M2, M3, P2	Middle-flow	Till 130 ml/min	Radial artery, saphenous vein
High-flow bypass	External carotid artery, Common carotid artery	M2, M3, P2	High-flow	Till 150 ml/min (RAG)	Radial artery, saphenous vein
	Vertebral artery (V3)			Till 250 ml/min (SVG)	
Intra-intracranial bypass	Intracranial arteries	M2, M3, A3, A4, PICA	Low-flow/Middle-flow/High-flow		+/-

**A3, A4** - anterior cerebral artery segments; **M2, M3, M4** –middle cerebral artery segments; **P2** – posterior cerebral artery segment; **AICA** - anterior inferior cerebellar artery; **PICA** - posterior inferior cerebellar artery.



The choice of bypass depended on a revascularized area and the decision was based on intraoperative Doppler flow measurements and angiographic images <sup>6,7,23</sup> as well as on preoperative tests for assessing compensatory collateral blood flow <sup>9</sup>. Intraoperative volumetric flow ultrasound fluorimetry was another important tool for determining the type of bypass in any given situation.

### The efficiency of CIA occlusion

As shown in Table 1, in the considered patient series, various occlusion techniques were used depending on complex MCA aneurysm localization: proximal occlusion (23%), trapping (19%), distal occlusion (10%), direct clipping (in 8%), clipping with reconstruction (19%), aneurysm resection (21%) and coiling (0.4%). The efficiency of aneurysm occlusion varied from 68 to 100% among different authors (see Table 2). In 5 of the 9 studies, residual aneurysm cavities were observed in the postoperative period. Zhu et al., 2013 had 11 residual aneurysms out of the 59 complex MCA aneurysms treated (19%), none of them requiring further surgical treatment, so only one patient underwent a reoperation during a two-year follow-up period <sup>4</sup>. According to Wessels et al., 2019, postoperative angiography at 3 - month follow-up revealed partial occlusion in 11 (22%) patients who also did not require reoperation <sup>8</sup>. In one patient, a residual aneurysm was a deliberate solution to allow for subsequent coiling <sup>2</sup>.

In the series by Kalani et al., 2012, 12 out of 16 (75%) aneurysms were completely occluded in the postoperative period. However, residual aneurysms were observed in 3 cases (two of them were subsequently clipped, and one – coiled) <sup>6</sup>.

In the series by Ravina et al., 2019, two residual aneurysms were observed. In one patient, the aneurysm was filled retrogradely

through an anastomosis to maintain perfusion of the perforating arteries. In the second - the residual aneurysm had a small calcified neck that was not compressed by the clip's jaws <sup>15</sup>. Radiographically a residual aneurysm is an aneurysm with a portion filled with contrast after clipping <sup>5</sup>. However, despite such intraoperative controls as ICG-VA and Doppler, the percentage of postoperative residual aneurysms varied from 4 to 19% in the series reported by Dellaretti et al., 2017 <sup>5</sup>. Atherosclerotic lesion/calcification of the aneurysmal walls and intraaneurysmal thrombotic masses created an obstacle for aneurysm complete occlusion after clipping <sup>24</sup>. In addition, complete and timely thrombosis in the aneurysm cavity did not always occur after proximal or distal complex MCA aneurysm occlusion. It was shown that the frequency of residual aneurysms increased with their size and the patient's age, the prevalence of atherosclerotic processes in the aneurysmal wall, as well as with the number of clips applied to the aneurysm, all of them causing an increased risk of incomplete occlusion <sup>5</sup>.

### Complications, mortality, and treatment outcomes

All the complications in the considered patient series can be divided into ischemic, infectious, hemorrhagic, and others (Table 4). Despite constantly improving surgical techniques and a variety of intra- and postoperative control methods, various complications occurred during complex MCA aneurysm treatment, most of them associated with the development of vascular thrombosis and ischemia <sup>23,25,26</sup>.

The most common cause of the complications was a stroke that developed either in the MCA territory or in the subcortical structures due to bypass occlusion or its inadequate functioning or impaired blood flow in the LSA.

**Table 4.** Complications of complex MCA aneurism treatment.

Complications	Zhu et al., 2013	Wessels et al., 2019	Natarajan et al., 2019	Meybodi et al., 2017	Kivipelto et al., 2014	Kalani et al., 2012	Wang et al., 2018	Ravina et al., 2019
Stroke, n	5	2	6	2	6	3	2	
Epidural hematoma, n			1	1				
Subdural hematoma, n			1		2			
Intracerebral hematoma, n	2		1		4			
Hemorrhage from cervical anastomosis, n		1						
Hydrocephalus, n					1	2		
Meningitis, n	3				5			
Pneumonia, n			1		6			
Epidural infection, n			1					
Seizures, n	2							
Deep venous thrombosis, n					1			
Suture sinus, n								1
Skin necrosis, n					1			

Ischemic disorders were observed almost in all groups by various authors (7 out of the 9). In 11 out of 26 cases (42.3%), ischemic disorders in the postoperative period were associated with bypass occlusion, (Table 5). Other reasons for ischemic disorders were SVG stenosis; bleeding from the anastomotic zone<sup>8</sup>; irreversible cerebral ischemia due to prolonged temporary clamping<sup>24</sup>; lack of revascularization of the second M2 branch of the MCA; perforators damage or vasospasm<sup>4,10,24</sup>.

According to Kalani et al., 2012 a stroke could also develop in a functioning bypass due to thrombotic masses from aneurysm cavity; temporary clamping; and inadequate blood flow through the bypass<sup>6</sup>. In addition to symptomatic anastomosis occlusions, there were asymptomatic cases that produced no ischemic disorders<sup>2,10</sup> (Table 5).

**Table 5.** The number of performed bypasses/ bypass occlusions vs. the number of strokes caused by bypass occlusion.

Authors, Year	Bypasses, n	Bypass occlusions, n	Strokes (all reasons), n	Strokes due occlusion, n	Asymptomatic bypass occlusion, n
Zhu et al., 2013	22	1	5	1	
Wessels et al., 2019	49	2	2	2	
Natarajan et al., 2019	52	1	6		1
Meybodi et al., 2017	30	3	2	2	1
Kivipelto et al., 2014	25	2	6	2	
Kalani 2012 et al.,	16	1	3	1	
Wang et al., 2018	12	2	2	2	

Infections were the second most common complications in the complex MCA aneurysms treated (see Table 4). Postoperative meningitis, pneumonia, and epidural infection requiring bone flap removal prevailed in this group. In most cases, these complications were cured with antibiotic therapy.

Hemorrhagic complications were also widespread in the patient series (5 out of the 9 cohorts). The most frequent manifestations were the formation of intracerebral, subdural, and epidural hematomas and bleeding from the anastomotic area (Table 4). In several cases, a reoperation was required to remove a hematoma.

In the series by Zhu et al., 2013, 2 patients developed seizures<sup>4</sup> another two - skin necrosis around the edges of the surgical wound, and one of them required skin transplantation<sup>7</sup>. In another series, two patients developed hydrocephalus, which was an indication for shunt system implantation<sup>6,7</sup>. In one case, a patient developed deep venous thrombosis of the lower extremities and pulmonary embolism<sup>7</sup> and another one – the wound separation followed by suture sinus formation treated conservatively in a course of 2 weeks<sup>15</sup>. In the considered patient series, the average mortality was 2.9% ranging from 2.4 to 6.9 % in different cohorts (Table 6).

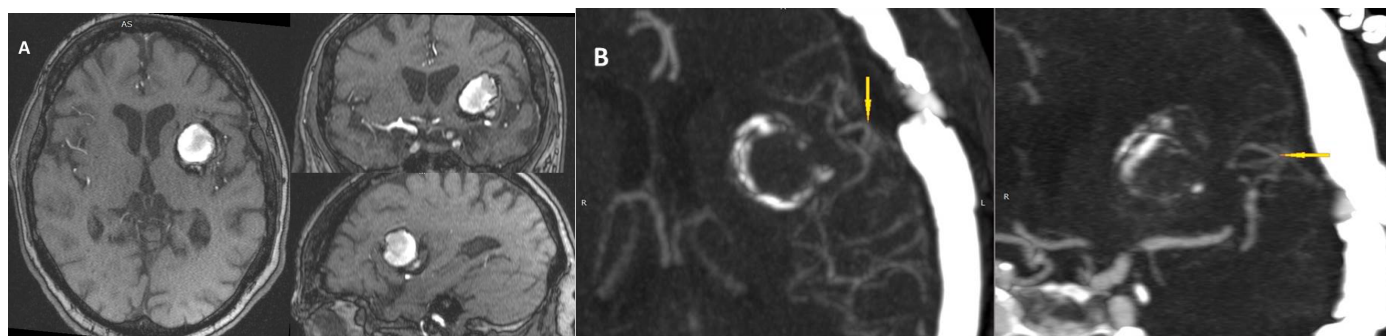
**Table 6.** Patient mortality after complex MCA aneurysm treatment.

Authors, Year	Stroke, n	Due to rupture of an aneurysm, n	Pulmonary embolism, n	Sepsis, n	Nonsurgical-related diseases, n
Zhu et al 2013		2			2
Wessels et al 2019	1		1		
Natarajan et al 2019				1	
Kivipelto et al 2014		1			

The most common reasons for patient mortality while complex MCA aneurysm treatments were aneurysm rupture and severe SAH (3 patients)<sup>4,7</sup>. In the late postoperative period, such reasons were pulmonary embolism and sepsis (2 patients)<sup>8,10</sup>. Ischemic strokes due to bypass occlusion occurred only in 1 patient in 7<sup>8</sup> (Table 6).

Even though a quarter of the patients in the series had ruptured aneurysms before surgery, the overall outcomes of surgical treatment were good, and in 211 patients (86.5%), they were assessed as 0-2 and 4 -5 points on the mRS and GOS scales, respectively (see Table 2). It is noteworthy that in the patients with unruptured aneurysms, the outcomes were better than in those with the SAH caused by a rupture. At the same time, the outcomes in patients with unruptured aneurysms were better than in those with SAH due to the ruptured aneurysm.

## Illustrative cases



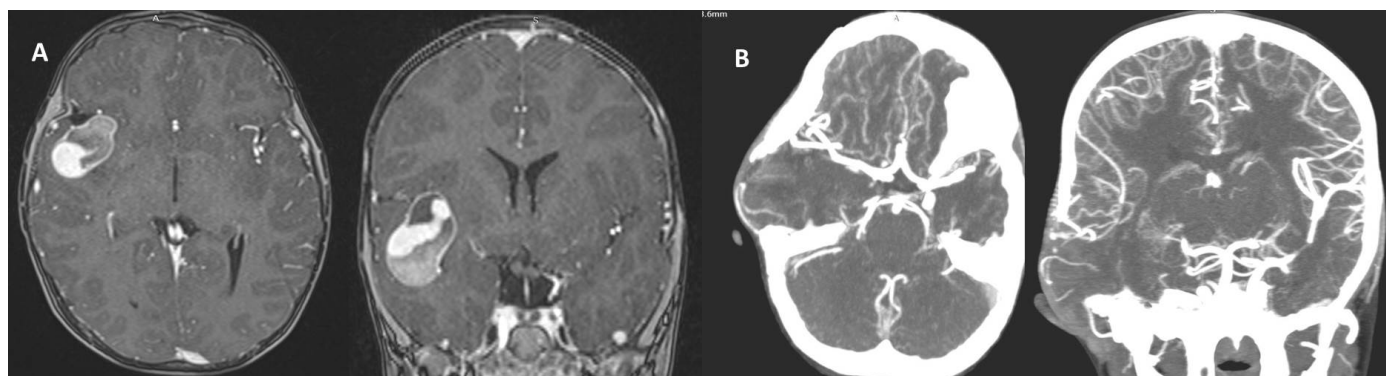
**Figure 1.** A 71-year-old woman with a giant thrombosed aneurysm in the M3 segment of the left middle cerebral artery (MCA). A-before treatment. B-after treatment: the arrow shows a functioning intra-to-intracranial microanastomosis.

### Case 1

A 71-year-old woman presented with a history of headaches and seizures she had had since 2013. She was diagnosed to have a giant thrombosed aneurysm in the M3 segment of the left middle cerebral artery (MCA). The aneurysm of 26-26 mm in size had calcinated wall and compressed the neighboring regions of the brain, causing edema and a moderate mass effect. The patient underwent left osteoplastic pterional craniotomy with intra-to-intracranial microanastomosis between the M3 segments of MCA, aneurysm trapping and thrombectomy from the aneurysm sac. The postoperative period was uneventful (**Figure 1**).

### Case 2

A 7-year-old boy presented with a partially thrombosed pseudotumor saccular aneurysm of 24x17 mm in axial size and 23 mm in vertical size of the temporal M2 branch of the right MCA. The patient underwent right osteoplastic pterional craniotomy with extra-to-intracranial microanastomosis between the frontal branch of the right superficial temporal artery (STA) and the M4 segment of the left MCA and microsurgical removal of the aneurysm. In the postoperative period, the patient developed a liquor cushion under the flap to regress later and a slight left hemiparesis. Postoperative brain MSCT showed the lumen of the MCA-STA bypass had not narrowed, and the aneurysm had obliterated (**Figure 2**).



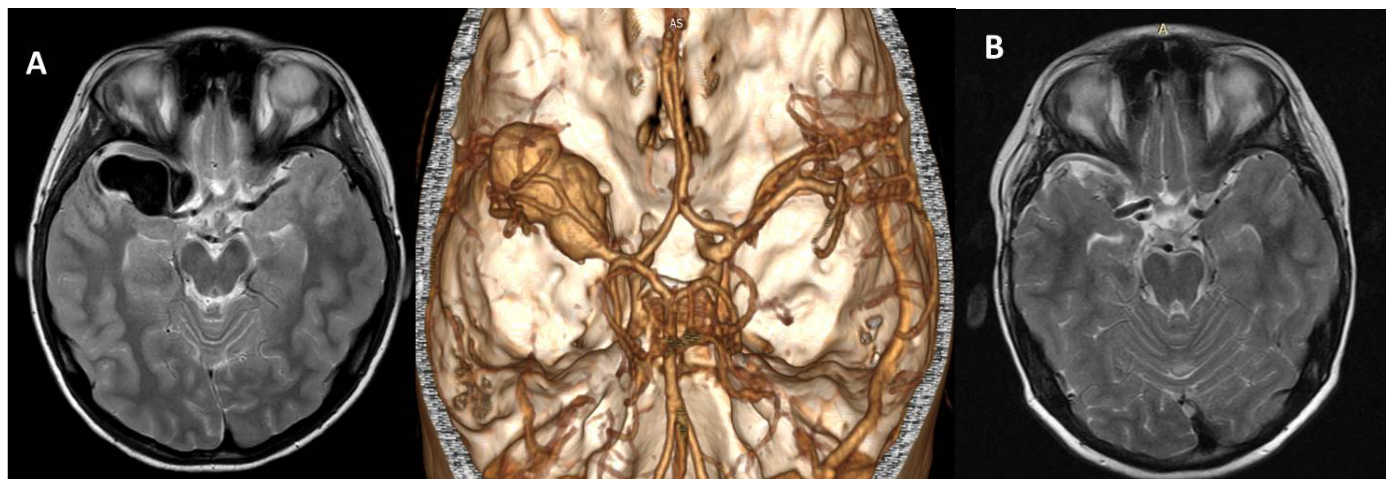
**Figure 2.** A 7-year-old boy with a partially thrombosed pseudotumor saccular aneurysm of the temporal M2 branch of the right MCA. A-before treatment. B-after treatment.

### Case 3

A 12-year-old boy presented with a history of headaches he had had since June 2019. Angiographic MRI and MSCT imaging of the patient's extra-and intracranial arteries detected a fusiform aneurysm of the M2 segment of the left MCA. Its maximum diameter was 17 mm, and the length – 36 mm. The patient underwent left osteoplastic pterional craniotomy with double-barrel extra-to-intracranial microanastomosis between the frontal and parietal branches of the left STA and the cortical segments of the left MCA.

The aneurysm was clipped. In the postoperative period, the patient's neurological status improved to match the preoperative level. Postoperative control imaging showed the aneurysm had completely obliterated while the bypasses had remained functional and patent (**Figure 3**).





**Figure 3.** A 12-year-old boy with a fusiform aneurysm of the M2 segment of the left MCA. A-before treatment. B-after treatment

## Conclusion

For the time being, microsurgical treatment of complex MCA aneurysms remains a method of choice if compared to the endovascular techniques<sup>12,27</sup>, so many centers still prefer surgical clipping to endovascular treatment<sup>12</sup> due to its low mortality and higher success rate in experienced hands and specialized centers<sup>27,28</sup>.

Nevertheless, recently we have seen a tendency to apply the multidisciplinary approach combining surgical and endovascular techniques for the treatment of complex MCA aneurysms<sup>29,30</sup>. Hybrid techniques make it possible to expand an intervention range due to a skillful combination of revascularization and endovascular occlusion techniques during one surgical session.

Treatment of CIAs and complex MCA aneurysms, in particular, is a difficult process requiring combining different surgical approaches in every individual case to achieve the main goal that is a good outcome, especially in the presence of ruptured aneurysms. Complicating the surgery significantly increases the risks of hemorrhagic and ischemic complications. In our opinion, in the presence of so many available techniques, the main purpose of a surgeon is to obtain the necessary results applying the simplest approaches. Following this paradigm in the treatment of complex MCA aneurysms allows one to avoid complications and reduce mortality.

Complex intracranial aneurysms are surgically demanding lesions. It is obvious that surgical planning and treatment of complex MCA aneurysms depends on their morphology, localization (M1 segment, bifurcation, or distal MCA segments), anatomical and angioarchitectonical features, and requires an individual approach to every patient. Careful preoperative planning, intraoperative hemodynamic (ICG-VA, contact Doppler) and electrophysiological assessment, adequate revascularization, and postoperative examinations (MSCT, MRI, angiography) will help to reduce the risk of complications and mortality in the patients.

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