



Bypass surgery of complex middle cerebral artery aneurysms—technical aspects and outcomes

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Abstract

Background The main challenge of bypass surgery of complex MCA aneurysm is not the selection of the bypass type, but the initial decision making of how to exclude the affected vessel segment from circulation. The aim of our study was to review our experience with the treatment of complex MCA aneurysms using revascularization and parent artery sacrifice techniques. Based on this, we aimed at categorizing these aneurysms according to specific surgical aspects in order to facilitate preoperative planning for these challenging surgical pathologies.

Methods We reviewed 50 patients with complex MCA aneurysms that were not clippable but required revascularization and parent artery sacrifice. We report the individual variations of surgical techniques, highlight the technical aspects, and categorize the aneurysms based on their location and orientation.

Results Of the 50 aneurysms, 56% were giant, 16% large, and 28% < 10 mm, but fusiform. Fourteen percent were previously treated endovascular. Four percent presented with SAH. Ten percent were prebifurcational, 60% involved the bifurcation, and 30% were postbifurcational. Both parent artery sacrifice and bypass strategies were tailored to the individual localization and anatomical relationship of the aneurysm and inflow/outflow arteries (38% proximal inflow occlusion, 42% aneurysm trapping, 20% distal outflow occlusion; 14% STA-MCA bypass, 48% interposition graft, 36%, combined/complex revascularization with reimplantation/in situ techniques). Good outcome (mRS 0–2) rates at discharge and at follow-up were 64% and 84%. Based on our analysis of individual cases, we categorized complex MCA aneurysms into six types and provide individual recommendations for their surgical exploration and treatment by revascularization and parent artery sacrifice.

Conclusion Complex MCA aneurysms are among the most challenging vascular lesions and afford highly individualized treatment strategies. Revascularization and parent artery sacrifice provide durable results that are superior to the natural history. Our classification provides a tool for planning and pre-surgical assessment of the intraoperative anatomy of complex MCA aneurysms, helping to assume possible pitfalls.

Keywords Complex aneurysms · Fusiform · Revascularization

Introduction

The majority of complex aneurysms is giant, fusiform, or partially thrombosed/calcified, with the need for sacrificing

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the diseased vessel segment and revascularizing the dependent vascular territory with a bypass, as the only durable strategy for aneurysm exclusion [21]. Complex MCA aneurysms are specifically complicated to treat, due to multiple perforators along the M1 segment, the limited accessibility of M1 and M2 branches frequently hidden behind the giant aneurysm mass, as well as the potential need for revascularization of multiple M2/M3 branches [6, 17].

Pre-operative planning must address two major questions. The first and most important question is “how to handle the aneurysm and the parent artery”. The most definitive treatment is trapping of the aneurysm by occluding both the proximal inflow and distal outflow segments, resulting in immediate exclusion of the diseased vessel segment. Trapping of the

parent artery is, however, not always possible. Examples include the involvement of perforating arteries or the inability to access all proximal and distal vessels at their inflow/outflow segments. In such cases, a proximal inflow or distal outflow occlusion has been proposed, especially in unruptured aneurysms. The occlusion of the proximal inflow vessel just before its entry into the aneurysm will result in retrograde, sluggish blood flow, and thrombosis of the aneurysm. Proximal occlusion, however, is not possible if the inflow segment is hidden behind a giant aneurysm mass, access to the inflow segment would significantly add to the invasiveness of the procedure and would risk injury to the fragile aneurysmal entry zone of the inflow segment, or a perforator-free zone is not available for placing the clip. In these cases, distal outflow occlusion may be preferred if all outflow segments can be visualized at the aneurysmal exit zone. This will result in antegrade, sluggish blood flow, and thrombosis of the aneurysm. Once it is clear how the aneurysm will be handled, the second question should be addressed, i.e. “how to revascularize the distal vascular territory”. Trapping and distal outflow occlusion necessitate a bypass to all outflow vessel segments, while proximal inflow occlusion necessitates a bypass only to one outflow vessel segment as the other segment(s) will be perfused via retrograde flow from the bypass.

The pertinent literature on complex MCA aneurysms mainly focuses on the ideal bypass technique. However, it is impossible to provide generalized recommendations since there is a large armamentarium of bypass strategies for revascularization and the technique to choose is influenced by the individual case and the surgeon preference [2, 6, 7, 9, 10, 12–14, 21, 23, 25]. In our eyes, the more relevant aspect to address in the preoperative planning is the anatomy of the diseased vessel segment, i.e., the location of the aneurysm as well as the anatomical relationship between the aneurysm and the afferent/efferent vessels. Therefore, a systematic approach and detailed preoperative planning of the strategy should prepare the surgeon for the complexity of the procedure and will significantly add to the success of surgery. Although contemporary 3D image reconstructions facilitate preoperative planning, the surgical decision making for complex MCA aneurysms largely depends on the anatomy and maneuverability of the aneurysm and its vessel branching anatomy from the surgeon’s intraoperative perspective [1, 9, 19]—factors that are not addressed well by virtual 3D images.

The aim of this study was therefore to review our experience with our subsequent series of complex MCA aneurysms, treated by parent artery sacrifice and bypass revascularization. In addition to reporting our surgical and clinical results, we aimed at providing a preoperative, standardized categorization for complex MCA aneurysms, anticipating the intraoperative vessel anatomy and appropriate exclusion strategy applied to the diseased vessel segment. The surgeon should have a field

manual prior to surgery as an aid to anticipate the key intraoperative findings. Here, we focused on the relevance of perforators, accessibility of the M1 and M2 branches, and possible anatomy-related challenges during the surgery.

Methods

We performed a retrospective analysis of our database of patients receiving cerebral bypass surgery between 2007 and 2018 in our institution. We filtered for patients with complex aneurysms of the MCA requiring cerebral revascularization and parent vessel sacrifice to achieve aneurysm occlusion. Mycotic aneurysms were excluded. All patients obtained MRI, CT, and DSA preoperatively and postoperatively. Bypass patency was assessed by ICG videoangiography and Doppler flowmetry intraoperatively. Surgical data was obtained from medical charts, operation notes, and intraoperative videos. Follow-up data was obtained at discharge and at 3–6 months postoperatively. Clinical outcome was assessed according to the modified Rankin Scale Score (mRS). Good outcome was defined as mRS 0–2.

Results

Patient characteristics

We identified 50 patients with complex MCA aneurysms requiring cerebral revascularization and parent artery sacrifice. Of those, 28 (56%) were giant (> 2.5 cm), partially thrombosed, and/or calcified aneurysms, 8 (16%) were large (> 1 cm), 14 (28%) were of normal size (<1 cm) but had a fusiform shape or affected the vessel segment so that clipping would have led to parent vessel occlusion. Mean age was 43 ± 22 years, 20 patients (40%) were female, and 30 were male (60%). The mean time of hospitalization was 16.4 ± 6.4 days. Seven patients were previously treated by endovascular means, six with conventional coiling, one by stent-assisted coiling. Two patients presented with subarachnoid hemorrhage (SAH). Five (10%) aneurysms were located in the M1 segment (prebifurcational), 30 (60%) aneurysms involved the MCA bifurcation (bifurcational), and 15 (30%) aneurysms were located at the M2/M3 level (postbifurcational).

Surgical and clinical outcomes

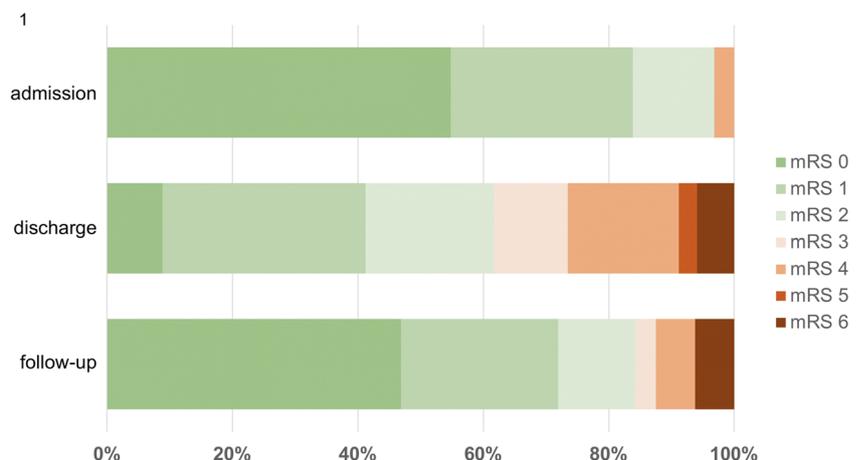
Aneurysms were excluded using the following strategies: 19 (38%) aneurysms with proximal inflow occlusion, 21 (42%) aneurysms were trapped, and 10 (20%) aneurysms with distal outflow occlusion. Postoperative DSA during the hospitalization period demonstrated complete aneurysms occlusion in 34

(68%) and partial occlusion in 16 (32%) patients. By definition, all aneurysms that were trapped demonstrated complete occlusion. In contrast, only 13 (54%) of the aneurysms with proximal/distal occlusion were completely occluded. Postoperative DSA after 3 months demonstrated complete aneurysm occlusion in 39 (78%) and partial occlusion in 11 (22%) patients, reflecting a significant amount of aneurysms with delayed occlusion and remodeling of their aneurysms in the cases where the aneurysms could not be trapped.

Cerebral revascularization was achieved using the following bypasses: 7 (14%) patients with single barrel or double barrel STA-MCA bypasses, 24 (48%) patients with extracranial-intracranial interposition grafts from the external carotid artery to M2 (radial artery or saphenous vein), and 18 (36%) patients with combined/complex revascularization techniques (reimplantation/transposition/in situ techniques). Intraoperative patency rate was 100% at the end of the procedure. Postoperative DSA during the hospitalization period revealed a patency rate of 96%. One bypass showed patency in ICG-VA during surgery but was occluded in the postoperative control-CT-angiography. In one patient, a severe hemorrhage from the cervical anastomosis occurred; after revision, the bypass was occluded. At follow-up, no further bypass occlusion was observed.

We assessed the clinical condition of the patients using the mRS at admission, discharge (mean 16 days after surgery), and at follow-up (mean 6 months after surgery) (Fig. 1). Median pre-treatment mRS was 0. However, two patients had initially suffered from severe SAH. Mortality was 4%. Reasons for mortality were one malignant infarction after bypass occlusion and one pulmonary embolism. Good outcome (mRS 0–2) rates at discharge and at follow-up were 64% and 84%, respectively, demonstrating significant recovery rates in the first 6-month period after surgery (Fig. 1). Excluding the SAH cases from the outcome analysis resulted in good outcome (mRS 0–2) rates at discharge and at follow-up of 74% and 90%, respectively.

Fig. 1 Modified Rankin scale prior to surgery, at discharge and follow-up



Illustrative cases

In the following, we present illustrative examples of different cases pointing out the pitfalls and differences between distinct types of complex MCA aneurysms. For every case, the pre- and postoperative DSA is shown, as well as a schematic picture of the intraoperative view and the bypass solution (Figs. 2, 3, 4, 5, 6 and 7).

Classification system for complex MCA aneurysms

From the review of the cases, we identified two important hallmarks for the treatment of complex MCA aneurysms that had major impact on the surgical strategy that was finally applied. First, the preservation of the M1 lenticulostriate perforators, and second, the surgical anatomy/orientation and accessibility of the inflow and outflow segments. Based on this, we set out to develop a classification for complex MCA aneurysms that would help the surgeon to identify these hallmarks based on preoperative imaging characteristics of the lesion and adjust the surgical strategy accordingly. The surgical strategy is the dissection of the aneurysm and inflow/outflow arteries, as well as the handling of the aneurysm and selection of strategy for parent artery sacrifice, followed by the decision of the revascularization strategy. In our classification system, complex MCA aneurysms are classified according to their localization and orientation as shown on ap and lateral views of the preoperative DSA.

We categorized the aneurysms according to the following criteria into a total number of 6 subcategories. Type I: Ia-fusiform/dysplastic M1 aneurysm without wall thrombus; Ib-fusiform M1 aneurysm with wall thrombosis. Type II: IIa-MCA bifurcation aneurysm pointing “upwards”; IIb-MCA bifurcation aneurysm pointing “laterally”; IIc, MCA bifurcation aneurysm pointing “downwards”. Type III: aneurysm of the M2 (or M3) segment without involvement of the bifurcation (Fig. 8a).

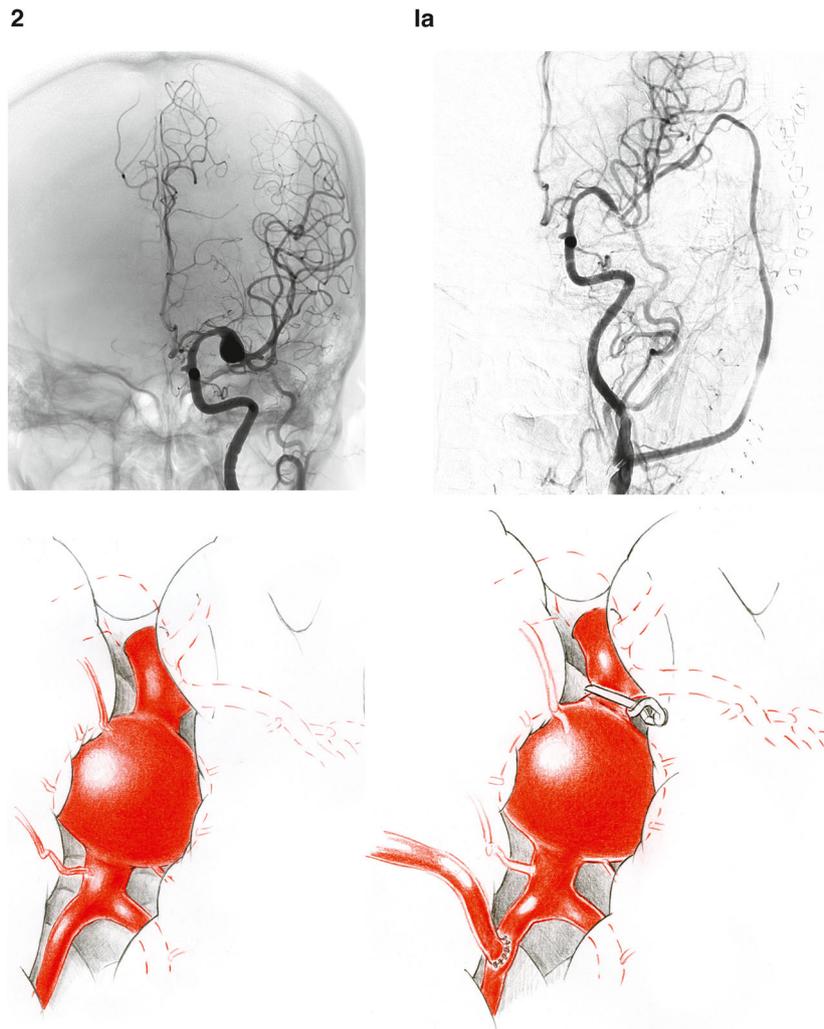


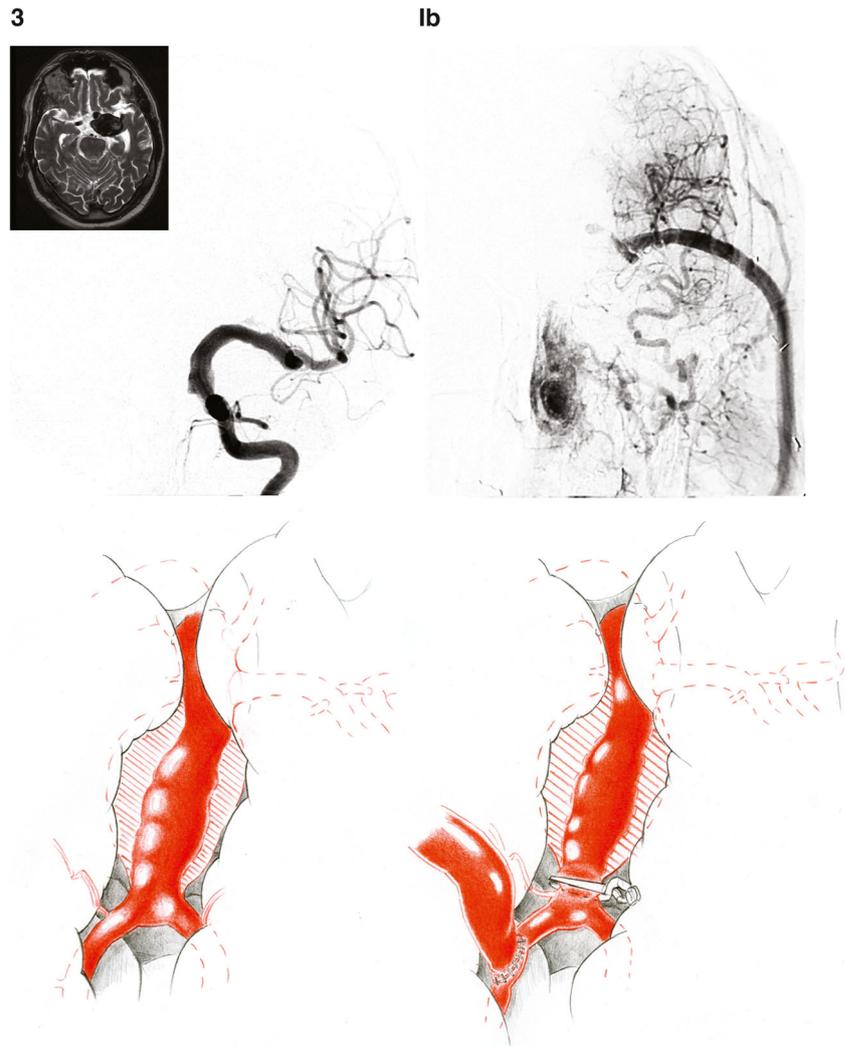
Fig. 2 Illustrative case 1: Pre- and postoperative angiography in the first row and a simplified drawing of the intraoperative view, the features of the aneurysm and the surgical solution for this fusiform M1 aneurysm. This 50-year-old female presented to our department without neurological deficits. She had a history of SAH 10 years ago, with clipping of a MCA aneurysm. The patient recovered well from the bleeding and returned to normal life. The follow-up MRI revealed a fusiform aneurysm of the M1 segment proximal to the clip, approximately 11 mm in size, without radiological signs of vessel wall thrombosis. Following transsylvian exposure, it became clear that M1 perforators were abundant and appeared to be functional. ICG videoangiography revealed unaltered perfusion of these perforating arteries and clip test occlusion under

electrophysiological monitoring confirmed the relevance of these vessels for capsular supply. Thus, it was clear that trapping was not possible and we opted for occlusion of the M1 inflow segment. For revascularization of the MCA bifurcation territory, we performed a radial artery graft bypass from the ECA to the more prominent temporal M2 segment. The postoperative angiography demonstrated bypass patency and subtotal thrombosis of the aneurysm with persisting retrograde perfusion of the M1 perforators. Unfortunately, despite this good angiographic result, the patient suffered from a delayed M1 perforator infarction (despite antiplatelet therapy) in the internal capsule with a right-sided hemiparesis. This course reflects how common the risk of perforator injury in M1 aneurysms is without intraaneurysmatic thrombosis

Type I aneurysms are located along M1 and are subdivided depending on the presence of an intramural thrombus. Type Ia aneurysms lack a thrombus and therefore, demonstrate functional M1 perforators, prohibiting a trapping of the aneurysm. In type Ib aneurysms, M1 perforators are not functional due to the thrombosis of the fusiform aneurysm wall, allowing trapping of the aneurysms. Type II aneurysms incorporate the MCA bifurcation and are subdivided depending on the accessibility of the M2 branches following the opening of the Sylvian Fissure. In type IIa aneurysms, the M2 branches are

on top of the aneurysm and can be easily controlled when manipulating the aneurysm. Since the M2 branches are readily visible following transsylvian exposure and thus can be revascularized and occluded close to their outflow from the aneurysm. Type IIa aneurysms that are most amenable for trapping. In type IIb aneurysms, the M2 branches are pushed apart into the insular sulci, resulting in a larger distance and are covered by the opercula. Here, the surgeon has to dissect far laterally. This is of relevance when planning revascularization. In type IIc aneurysms, the M2 branches are hidden

Fig. 3 Illustrative case 2: Pre- and postoperative angiography in the first row and a simplified drawing of the intraoperative view, the features of the aneurysm and the surgical solution for this partially thrombosed M1 aneurysm. This 25-year-old patient presented with a partially thrombosed incidental fusiform M1 aneurysm. DSA confirmed the giant dissecting, serpentine aneurysm with a large proportion of aneurysmal wall thrombosis. Following aneurysm exposure, the M1 perforators could be identified, but showed no functional perfusion. For aneurysm occlusion, we performed a saphenous vein graft high flow bypass from the ECA to one M2 segment before distal occlusion. Proximal occlusion was not possible due to inaccessibility of the inflow segment. Postoperatively, the patient showed no new deficit. The patient was discharged without any complications. The follow-up DSA proved bypass patency and aneurysm occlusion



behind the aneurysm. Especially in giant and thrombosed aneurysms, it is not possible to control these M2 branches in their proximal segment and bypasses have to target the distal M2 segments. As a consequence, since the M2 branches are (in part in type IIb and completely in type IIc) hidden behind the aneurysm where the large thrombotic/calcified mass does not allow for control of the outflow segments of the M2 branches, type IIb and type IIc aneurysms are less amenable for aneurysm trapping. Type III aneurysms are along the M2/M3 branches. Here, the Sylvian Fissure has to be opened far distally, afferent and efferent vessel can be well controlled, and trapping is the primary goal.

The different aneurysm types also vary in respect to the bypass strategies applied (Table 1). Type I a/b and type III aneurysms can be successfully treated by straightforward EC/IC bypass strategies. Here, standard flow and intermediate flow bypass grafts are used to revascularize the distal territory by a single M2 anastomosis. The decision whether the STA or radial artery are used as grafts is dependent on the flow requirements—when in doubt, a radial artery is used. In

contrast, treatment of type II aneurysms often necessitates more complex revascularization techniques, such as Y-grafts, in situ anastomoses, vessel transpositions, or re-implantation techniques. This is since we primarily aim at trapping the aneurysm or at least occluding the (sometimes up to 4) M2 outflow vessels.

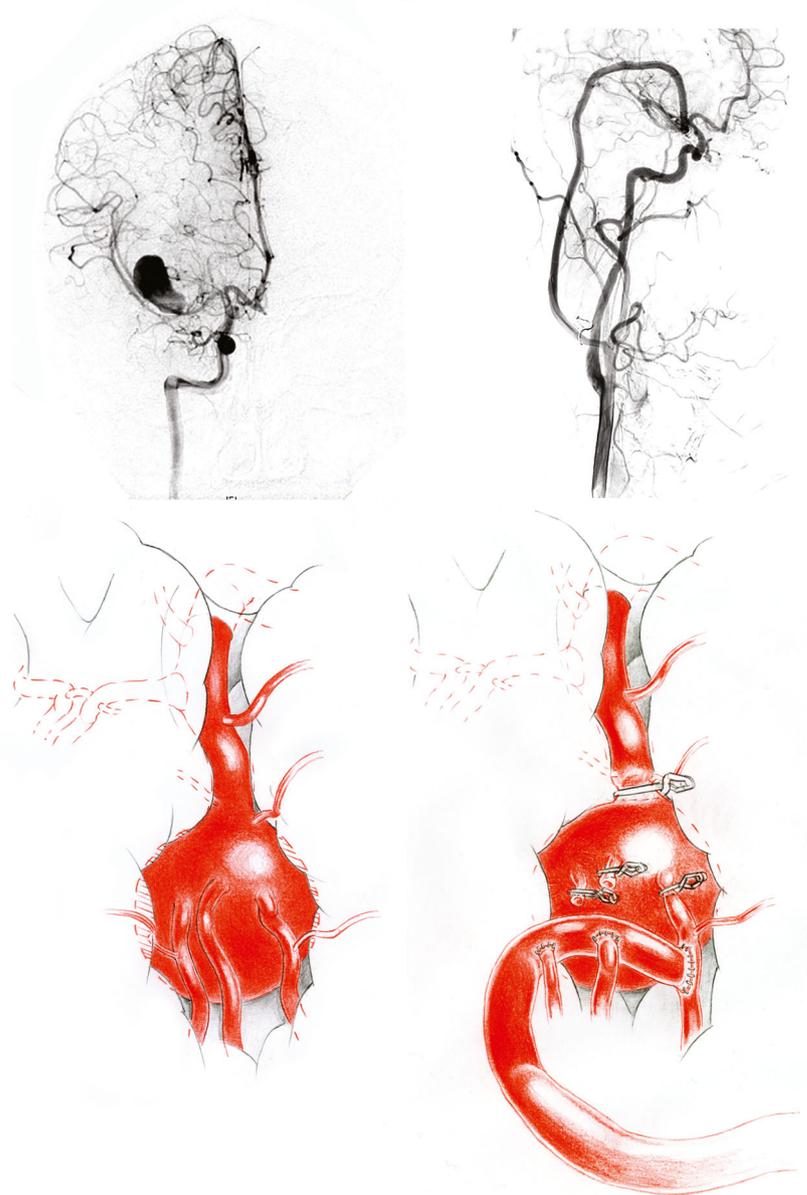
Discussion

In this manuscript, we have described a series of 50 consecutive complex MCA aneurysms that could not be clipped and required revascularization and parent artery sacrifice. The surgical and clinical results demonstrate durable results and outcomes that are superior to the natural history of the lesions. The second focus of this report was to highlight the technical aspects in planning and execution for these demanding surgeries, especially in cases of giant, often partially thrombosed or calcified aneurysms. As an orientation, we have designed a classification system, which would help the surgeon to pre-

Fig. 4 Illustrative case 3: Pre- and postoperative angiography in the first row and a simplified drawing of the intraoperative view, the features of the aneurysm and its relation to the M2 branches as well as the surgical solution for this bifurcational MCA aneurysm. This 40-year-old woman presented with an incidental giant aneurysm of the left MCA bifurcation pointing *upwards*, with M2 branches *below* the aneurysm in the ap view. Following opening of the Sylvian Fissure, the three M2 branches were readily visible, passing on the top of the aneurysm's sac with full control of the outflow segments. We therefore decided to trap the aneurysm and aimed to revascularize the M2 segments using a multiple re-implantation strategy. To this end, we used a 40-cm saphenous vein graft bypass from the left ECA, disconnected the two frontal M2 branches at the outflow segments, and reimplanted them into the saphenous vein graft. The graft was then anastomosed to the temporal M2 branch in an end-to-side fashion followed by completing the trapping of the aneurysm by proximal occlusion. Postoperatively, the patient showed no new deficit. The patient was discharged without any complications. The follow-up DSA proved bypass patency and aneurysm occlusion

4

IIa



operatively anticipate the anatomic relationship between the aneurysm, the M2 branches, the incorporated perforators, and the accessibility of the M1 inflow and M2 outflow segments. Therefore, we attempted to translate our experience into a simple classification system based on information from the preoperative angiography. Our series complements previous reports that focused on the selection of the bypass technique at the pre-bifurcation, bifurcation, and post-bifurcation levels [24, 26].

The rupture rate of MCA aneurysms increases with size. The very large and giant aneurysms, mostly partially thrombosed and/or calcified, which account for the largest

proportion of complex MCA aneurysms (72%), are associated with a 5-year rupture rate of 18 to 40% [8, 11]. The associated mortality and morbidity with a rupture are accordingly high. Our mortality rate of 4%, in contrast to this, is relatively low. Ninety-one percent of the elective patients have a favorable outcome 6 months after surgery. The patient outcome as well as the patency rate are comparable to previous reports upon surgical treatment of complex MCA aneurysms [24]. Endovascular treatment of complex MCA aneurysms, in contrast, is associated with a failure to control and cure the aneurysm, characterized by retreatment rates of up to 46% in large and giant MCA aneurysms, and often less favorable

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IIb

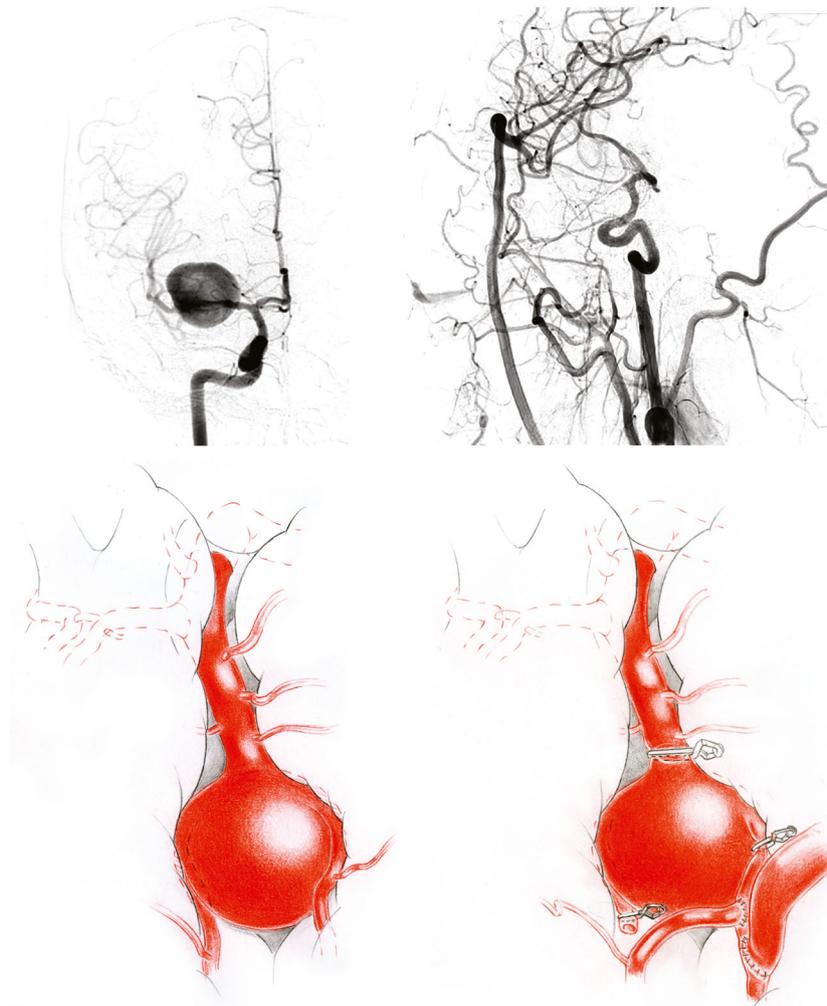


Fig. 5 Illustrative case 4: Pre- and postoperative angiography in the first row and a simplified drawing of the intraoperative view, the features of the aneurysm and its relation to the M2 branches as well as the surgical solution for this bifurcational MCA aneurysm. This 33-year-old man had undergone MRI due to chronic headaches for the last years. MRI revealed a giant MCA bifurcation aneurysm pointing *laterally* with M2 branches *parallel* to the aneurysm on the ap view. When opening the Sylvian Fissure, both M2 branches were pushed apart and located within the frontal and temporal insular sulcus, demanding a wide mobilization of the frontal and temporal opercula to gain control over the M2 branches. The temporal M2 branch was readily visible and the outflow segment could be well controlled. In contrast, the frontal M2 branch was more

difficult to control since its outflow was hidden behind the frontal part of the aneurysm. For revascularization, we performed a saphenous vein graft bypass from ECA to the temporal M2 branch. Subsequently, the frontal M2 branch was disconnected at the outflow zone, transposed, and reimplanted into the temporal M2 branch. Note that the site of reimplantation was proximal to the vein anastomosis so that the saphenous vein bypass could supply the temporal M2 territory while performing the M2-M2 reimplantation. The aneurysm was finally trapped. Postoperatively, the patient showed no new deficit. The patient was discharged without any complications. The follow-up DSA confirmed bypass patency and aneurysm occlusion

outcomes. In giant aneurysms, both endovascular treatment and conventional clipping are independent risk factors for failure to cure and need for retreatment [3, 4, 18].

Our series demonstrates the positive neurological improvement after postoperative deterioration, comparable to other neurosurgical interventions with a high complexity like in insular glioma [15]. The complete aneurysm occlusion rate in our series was very high (78%) compared to other treatment strategies [18]. Although distal and proximal occlusion will

not lead to direct aneurysm occlusion in all cases, there is a high amount of aneurysm occlusion in the first month. Retreatments have not been necessary during our follow-up period. Overall, the outcome and occlusion rates in our series support the feasibility of cerebral revascularization for aneurysm occlusion in complex MCA aneurysms. Of note, care should be taken in translating the concepts of proximal/distal occlusion strategies to ruptured aneurysms. It is obvious that in an acutely ruptured complex MCA aneurysm, the risk of

6

IIc

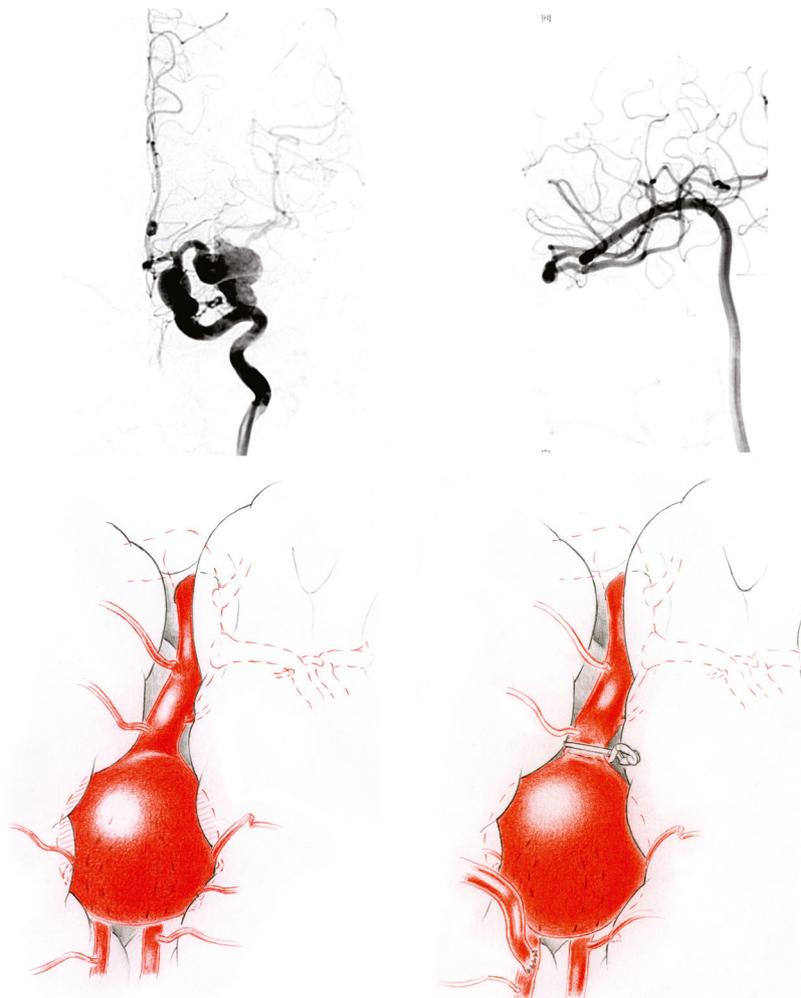


Fig. 6 Illustrative case 5: Pre- and postoperative angiography in the first row and a simplified drawing of the intraoperative view, the features of the aneurysm and its relation to the M2 branches as well as the surgical solution for this bifurcational MCA aneurysm. A 48-year-old woman with a giant aneurysm involving the MCA bifurcation was pre-treated by endovascular coiling. The follow-up MRI revealed reperfusion of the aneurysm. The preoperative DSA revealed an aneurysm pointing *downwards*, with M2 branches *above* the aneurysm in ap view. When opening the Sylvian Fissure, the two M2 branches were hidden behind the aneurysm mass. The intraluminal thrombus and coil material did not allow for mobilization of the aneurysm in order to visualize the M2

outflow segments. It was also evident that the first M3 branches originated from these inaccessible M2 segments. A safe disconnection at the M2 outflow segments was therefore impossible and prevented the trapping of the aneurysm. We therefore aimed for proximal occlusion of the M1 inflow zone and prior to that we performed revascularization with a radial artery graft from the ECA to a distal M2/M3 segment, surfacing distally to the aneurysm within the Sylvian Fissure. The patient was discharged without complications. The follow-up DSA confirmed bypass patency and subtotal (95%) aneurysm occlusion with retrograde filling of the non-revascularized M2 branch.

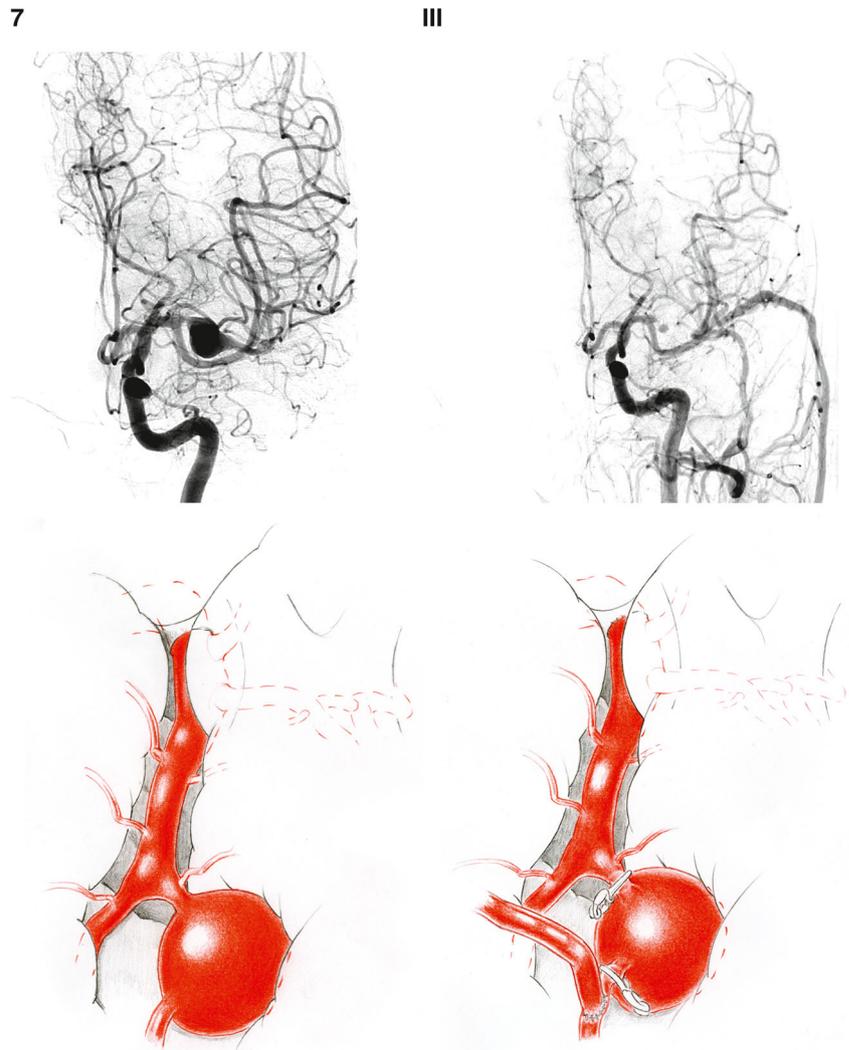
perforator ischemia from trapping has to be weighed carefully against the risk of re-rupture if the aneurysm is not immediately excluded from the circulation.

The categorization of M1 aneurysms into type Ia and type Ib aims to preserve functional perforating arteries arising from the M1 segment [19, 22]. Type Ia aneurysms demonstrated functional M1 perforators, prohibiting a trapping of the aneurysm. Our illustrative case 1 (Fig. 2) indicates the risk of occluding M1 aneurysms when a vessel wall thrombus is lacking. In type Ib aneurysms, M1 perforators are not functional anymore due to the dissection/thrombosis formation

within the fusiform aneurysm wall, allowing trapping of the aneurysm without causing a capsular infarction, although in our case, the inflow segment was not accessible due to the space-occupying effect of the aneurysm itself. However, we strongly recommend to use caution by implementing electrophysiological monitoring during test trapping of the aneurysm.

The categorization of MCA bifurcation aneurysms into types IIa-c aims at predicting the relationship between the aneurysm sac and the M2 outflow segments from the surgeons view, as well as their accessibility within the Sylvian Fissure

Fig. 7 Illustrative case 6: Pre- and postoperative angiography of the first row and a simplified drawing of the intraoperative view and the surgical solution for this postbifurcational aneurysm. A 15-year-old boy suffered from recurrent transitory ischemic attacks (TIA). The diagnosis showed a large left-sided fusiform aneurysm of the frontal M2 segment. The Sylvian Fissure had to be opened widely. The M2 inflow and outflow segments could be easily identified which allowed trapping of the aneurysm. Therefore, we performed revascularization of the M2 territory with a radial artery graft bypass from the ECA to the M2 outflow segment, followed by trapping of the aneurysm. Postoperatively, the patient showed no new deficit. The patient was discharged without any complications. The follow-up DSA proved both bypass patency and aneurysm occlusion



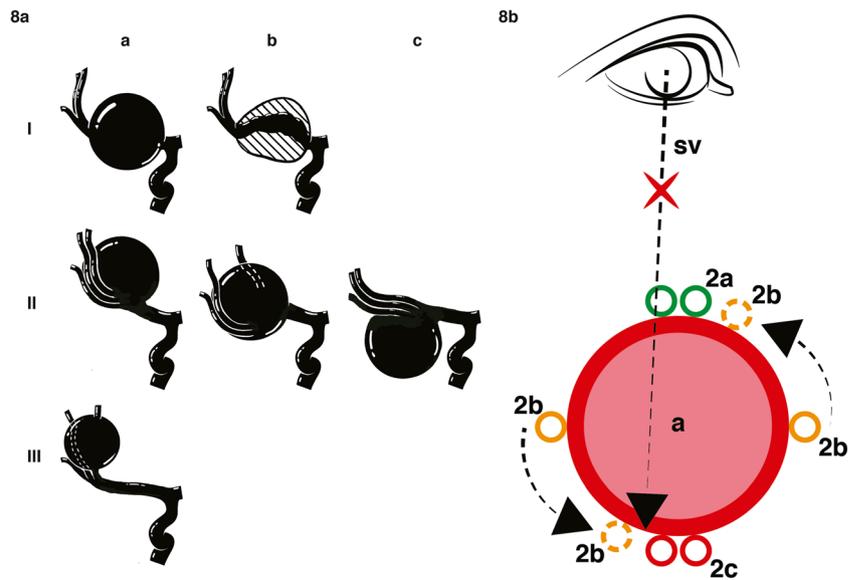
(Fig. 8b). In type IIa aneurysms, the M2 branches are on top of the aneurysm and can be easily controlled when exiting the aneurysm. In type IIb aneurysms, the M2 branches are pushed apart into the temporal and frontal insular sulcus and covered by the respective opercula. Here, the surgeon must dissect far laterally and the distance between the M2 branches may be so large that the anastomoses can only be established at the distal M2 segments, especially if the M2 branches are rotated around the equator of the aneurysm bringing one M2 outflow segment behind the aneurysm sac. In type IIc aneurysms, the M2 branches are hidden behind the aneurysm—this is the most complex scenario, as in giant and thrombosed aneurysms, it is not possible to control these M2 branches at the level of their outflow segment.

In type III aneurysms, both the proximal inflow segments and distal outflow segment(s) can be controlled easily following a wide dissection of the Sylvian Fissure. Relevant perforators usually do not exist at this level and the aneurysm can, therefore, be trapped. In some cases, the aneurysm can be even

excised, and the proximal and distal vessel can be anastomosed in an end-to-end fashion.

In the past, the roles of fluorescence videoangiography and intraoperative flow measurements by Doppler sonography have been discussed for deciding about the revascularization strategy and the graft selection. Both ICG and fluorescein videoangiography have been proven to be an essential technique in assessing the patency and function of bypass anastomoses [16, 18, 19]. Fluorescence videoangiography can also be useful for identifying the distal M3/M4 branches that need to be targeted with the (STA) bypass in order to revascularize a certain vascular territory [5]. However, fluorescence videoangiography, due to its non-quantitative read-out, does not help in deciding which donor vessel to use and how to replace flow demand most properly. This is why intraoperative flow measurements using quantitative Doppler-based systems are discussed as an adjunct to decide which graft is needed as donor to revascularize a certain territory [2, 20]. However, while intraoperative flow measurements are very

Fig. 8 **a** Schematic illustration of the MCA aneurysm classification proposed in this manuscript in ap view. **b** Illustration of the surgeons' view on the aneurysm in relation to the M2 branch anatomy in type 2 aneurysms



useful in quantitatively assessing graft flow and deciding whether the bypass function is sufficient [24] deciding at the spot which graft to use for the anastomosis is not optimal for preparation and planning of the procedure. First, the decision on which donor vessel to use and prepare has to be made prior surgery, where our classification provides orientation. As a rule of thumb, we use a radial artery graft when the whole MCA territory has to be revascularized via a single anastomosis, e.g., for type 1 MCA aneurysms; we would not rely on a STA graft in this case (which might raise controversy); we use STA grafts, giving that the size is acceptable, for revascularizing M2/M3 territories, e.g., for type 3 aneurysms; we use saphenous vein grafts for complex combinations, re-implantation strategies, or Y-grafts, simply because of the length of the graft needed (up to 40 cm), e.g., for type 2 aneurysms. And apart from that, combinations can be used as needed. Second, not every surgeon has quantitative flow measurements at hand, and certainly, they are not a prerequisite to perform these kinds of surgeries.

It is difficult to devise a guideline for revascularization strategies in the context of complex and giant MCA aneurysms as the decision regarding the best bypass strategy will remain a case-to-case decision. Nevertheless, the following recommendations can be derived from our field manual.

Type Ia and Ib aneurysm necessitates a bypass to one M2 branch only and perfusion of the MCA bifurcation and the other M2 segment(s) will be achieved via retrograde flow distal to the aneurysm. Since this bypass needs to supply the whole MCA territory, we strongly recommend using a large caliber graft with a proximal anastomosis at the ECA. In type IIa aneurysms, where trapping is the primary goal either variants of double barrel bypasses (2× STA, STA + RAG, Y-RAG, or SV graft) or combination of a large caliber EC/IC bypass with in situ strategies (re-implantation interposition, side-to-side techniques) will be applied. In type IIb aneurysms, the M2 outflow segments are the furthest away from each other, and therefore, the surgeon will have to revascularize the M2 segments separately in most cases, e.g. by variants of double barrel bypasses (2× STA, STA + RAG, Y-RAG, or SV graft). In some cases, however, a transposition of one M2 segment is still feasible as illustrated in our case 4. This is impossible in type IIc aneurysms where either only one bypass to one M2 segment is indicated if the aneurysm is to be treated by proximal inflow occlusion or where separate revascularization of all M2 segments is indicated if aneurysm trapping is the goal. In type III aneurysms, a single/double barrel STA-MCA bypass is the most straightforward method to revascularize the distal M3 branches. In individual cases,

Table 1 Percentage for the different revascularization strategies among the different aneurysm types

	1a	1b	2a	2b	2c	3
EC-IC one anastomosis	100%	100%	43%	50%	54%	91%
Combined revascularization > 1 intracranial anastomosis			57%	50%	46%	
In situ bypass alone						9%

excision of the aneurysms and end-to-end re-anastomosis is a (more challenging) alternative.

In summary, our classification provides a tool for surgical planning and pre-surgical assessment of the intraoperative anatomy of complex MCA-aneurysms which will determine the individual surgical therapy.

Compliance with ethical standards

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

For this type of study, formal consent is not required.

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