ORIGINAL ARTICLE - VASCULAR NEUROSURGERY - ANEURYSM

Protective STA-MCA bypass to prevent brain ischemia during high-flow bypass surgery: case series of 10 patients

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Abstract

Background High-flow extracranial-intracranial bypass is associated with a significant risk of ischemic stroke. The goal of this study is to evaluate the effectiveness of STA-MCA bypass preceding a high-flow bypass as a means of protecting the brain from ischemia during the high-flow bypass anastomosis in patients with otherwise untreatable aneurysms.

Materials and method This prospective study included 10 consecutive patients treated for complex/giant aneurysm using a previous combined STA-MCA bypass and high-flow EC-IC bypass between June 2016 and January 2018 when classical endovascular or microsurgical exclusion was estimated too risky. Early cranial Doppler, MRI, CT scan, and conventional angiography were performed in each patient to confirm patency of bypasses, measure flow in the anastomoses, detect any ischemic lesions, and evaluate exclusion of the aneurysm.

Results The mean age at treatment was 55 years (range 34 to 67). The mean time of microsurgical procedure was 11 h (range 9 to 12). In all patients, the high-flow bypass was patent intraoperatively and complete occlusion of aneurysm was obtained. No ischemic lesions were noted on early MRI. One patient died from a large hemispheric infarction related to a common carotid artery dissection 10 days after the microsurgical procedure and immediate postoperative epidural hematoma was noted in one other patient.

Conclusion In this study, we described the use of a protective STA-MCA bypass, performed prior to the high-flow bypass, in order to reduce the risk of perioperative ischemic lesions without increasing the morbidity of the surgical procedure. This treatment paradigm was feasible in all ten patients without complications related to the STA-MCA anastomosis.

Keywords Aneurysm · High-flow · Protective bypass · Sta-mca anastomosis · Ischemia

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Introduction

The "gold standard" for the treatment of most large/giant/ and/or complex aneurysms remains is either surgical clipping or endovascular embolization. In certain cases, clipping or coiling are not feasible. In such cases, a high-flow extracranial-intracranial (EC-IC) bypass following by trapping of the parent artery may be a valuable therapeutic option [2, 23]. Nevertheless, this procedure is associated to a significant morbidity especially as a result of the occurrence of ischemic lesions during or after microsurgical procedure [2] . Occlusion of the parent artery is performed once the bypass procedure is completed and the bypass patency is confirmed. Both surgical (in the same surgical setting) or endovascular occlusion (after surgery) are accepted techniques [12]. The high-flow bypass procedure, usually from external

carotid artery (ECA) via a graft to middle cerebral artery (MCA), requires a transient interruption of the flow in the recipient artery (M2 or M3 segments of MCA) during the anastomosis. This temporary occlusion of a relatively large artery is not without risk. The likelihood of cerebral ischemia increases with the duration of anastomosis [19] and therefore the occlusion time should be kept as short as possible without compromising the quality of the anastomosis. In order to maintain some distal flow in the MCA territory during the temporary occlusion of the M1 or M2 segment, we perform a superficial temporal artery (STA) to cortical MCA branch bypass prior to performing the high-flow bypass (Fig. 1). This "protective" STA-MCA bypass results in some perfusion in the distal MCA territory and decreases the risk of iatrogenic ischemic lesions during the time of ECA-MCA is performed. Moreover, it adds to the overall perfusion of the MCA territory once the parent artery and aneurysm are occluded.

The goal of this study is to evaluate the effectiveness of STA-MCA bypass preceding a high-flow bypass as a means of protecting the brain from ischemia during the high-flow bypass anastomosis in patients with otherwise untreatable aneurysms.

Materials and method

Population

This prospective study included 10 consecutive patients treated for complex/giant aneurysm using combined low flow and high-flow EC-IC bypass. The patients were operated on in two different institutions (Antwerp University Hospital and Lille University Hospital) between June 2016 and January 2018. Ethics approval was obtained from the local institutional review board, and written informed consent was obtained from patients. One male and nine female patients underwent the procedure at a mean age of 55 years (range 34 to 67) at treatment. The clinical and neurological conditions of the patients and the type of aneurysm and its treatment are presented in Table 1.

The treatment strategy was systematically discussed and decided in multidisciplinary staff including neurosurgeons, neuroradiologists, and intensivists. All patients had a clinical examination performed by a senior neurosurgeon before and after the treatment. Age at diagnosis, medical history, neurological status, and the American Society of Anesthesiology (ASA) score [20] of each patient were recorded. In patient with a ruptured aneurysm, initial WFNS (World Federation of Neurological Surgeons) score

Fig. 1 STA-MCA (M3 and M4 segments) anastomosis (a, b) is performed before EC-IC high-flow procedure in order to protect brain from ischemia during receptor artery (M1 or M2 segments) clamping (c). Exclusion of giant MCA aneurysm is possible at the end of intervention (d)
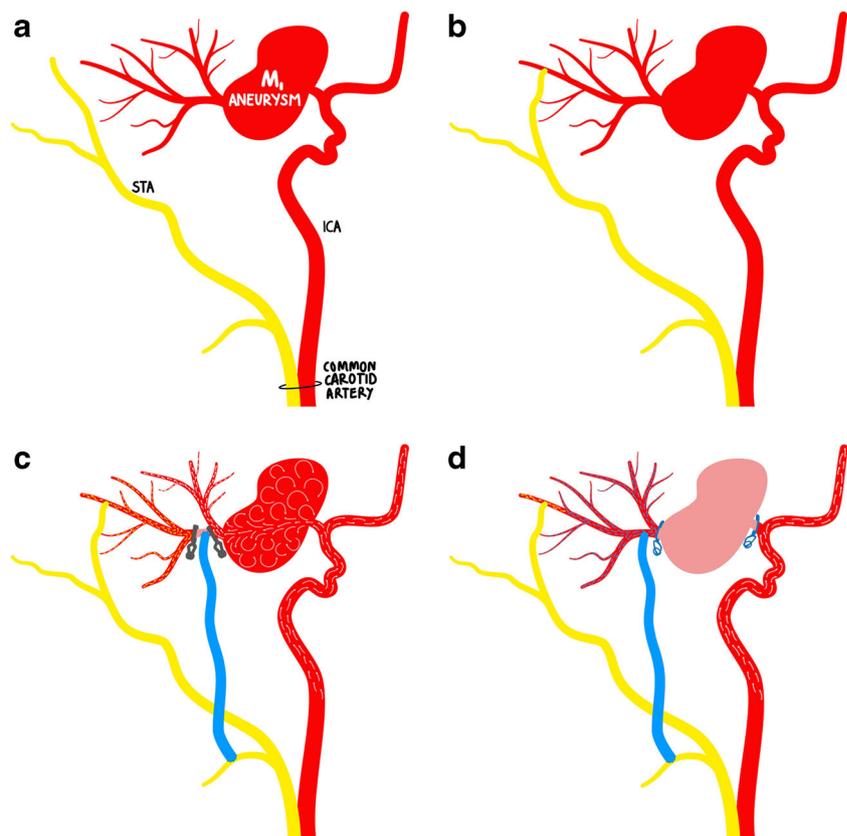
Table 1 Population data

Patient	Age at treatment	Aneurysm location	Ruptured aneurysm	Preoperative mRS	Endovascular exclusion after bypass	Complete exclusion	mRS 3 months after treatment
1	67	ICA bifurcation	+	3	–	+	3
2	66	MCA bifurcation	–	1	–	+	6
3	34	ICA intracavernous	+	4	+	+	3
4	50	ICA ophthalmic aneurysm	–	0	–	+	1
5	59	ICA intracavernous	–	1	+	+	1
6	61	MCA bifurcation	+	1	–	+	1
7	56	ICA	–	2	–	+	2
8	57	MCA bifurcation	–	2	+	+	2
9	51	MCA bifurcation	–	2	–	+	2
10	50	MCA bifurcation	–	0	–	+	0

[11] was recorded. The size and location of the aneurysm as well the angioarchitecture were evaluated on a conventional cerebral angiography and on a magnetic resonance imaging (imaging). Diameters of STA branches diameters were recorded by conventional external carotid angiogramm. Calcification of aneurysm wall and intrasaccular thrombus were documented using cranial computed tomography (CT) scanning and MRI. Venous Doppler and cervical Doppler allowed for the evaluation of venous graft quality (ulnar vein) and the evaluation of the internal carotid artery (ICA) and ECA. Exclusion of the complex/giant aneurysm by endovascular treatment or direct microsurgical neck clipping was evaluated by both neurosurgeons and neuroradiologists. When classical endovascular or microsurgical exclusion was estimated too risky, a previous combined STA-MCA bypass and high-flow ECA-MCA bypass is decided before internal carotid artery (ICA) or proximal MCA occlusion. Concerning the patients with ICA aneurysms, Balloon Occlusion Test was not tolerated and Flow diverter was not indicated because of vessel anatomical conditions as ICA cavernous segment too long or dysplasic.

Surgery

The patients were operated on under general anesthesia in supine position, with the head turned to the contralateral side fixed in a Mayfield clamp. The graft site for harvesting the vascular graft (i.e., ipsilateral arm) was draped simultaneously with the cranium and the cervical region. The STA was localized using palpation and portable continuous wave Doppler ultrasonography, and its course marked on the skin. Incisions and relevant blood vessels were marked on the skin. Incision lines were not infiltrated, to prevent spasm of the arteries.

A frontotemporal incision was made, careful to preserve STA integrity. Skin and subcutis were dissected and reflected caudally. A frontotemporal craniotomy over the Sylvian fissure was

performed, and the dura was opened to detect a suitable recipient M3-M4 cortical artery. Such arteries can be located superior or inferior to the Sylvian fissure. Once the recipient artery was identified, the STA was dissected. Depending on the length and diameter of the STA, either frontal or parietal branches were carefully dissected free, distally cut, and proximally clipped with a temporary aneurysm clip. When the M2-M2 "side to side" anastomosis was considered in the surgical strategy and/or good anatomical conditions (multiple branches of STA and good diameter of the recipient arteries) were present during procedure, two "protective" STA-MCA bypasses were performed.

Meanwhile, another surgeon microsurgically prepared the venous graft. All branches of the vein were occluded by clips or microsutures and cut. The distal and proximal ends of the vein were marked.

The Sylvian fissure was widely split to identify the appropriate M1 or M2 MCA segment. The recipient cortical artery (or arteries) were dissected free from the overlying arachnoid and isolated with a rubber sheet. Care was taken not to obscure the view of the Sylvian fissure, necessary for the high-flow bypass procedure, with the STA-MCA anastomosis. The cortical artery was temporarily clipped with a small aneurysm clip and arteriotomy was performed. Subsequently, an end-to-side anastomosis was performed of the STA to the cortical branches using microneurosurgical techniques with interrupted 10–0 nylon sutures. During temporary clipping, the blood pressure was raised to normotensive levels and barbiturates were administered. The patency of STA-MCA anastomosis was confirmed by intraoperative indocyanine green videoangiography.

Next, the high-flow bypass was performed. Ipsilateral common, internal, and external carotid arteries were dissected and end-to-side anastomosis was performed between the distal venous graft and a branch of the ECA using interrupted 9–0 nylon sutures. The vascular graft was then tunneled pre- or postauricularly to the cranium. The proximal venous end was

then anastomosed end-to-side to the M1 or M2 segment of the MCA using interrupted 10–0 nylon sutures.

The patency of STA-MCA and ECA-MCA bypasses was confirmed by intraoperative indocyanine green videoangiography. If the bypasses were patent, the parent artery of the aneurysm (ICA or MCA) was occluded with an aneurysm clip when technically feasible. The wound was closed in a standard fashion, making sure not to compromise the bypasses.

If parent artery occlusion was not performed during surgery, endovascular occlusion was performed within 24 h after the procedure.

Postoperative evaluation

Early (< 7 days) postoperative clinical and neurological examination was performed by a senior neurosurgeon. Early cranial Doppler, MRI, CT scan, and conventional angiography were performed in each patient to confirm patency of bypasses, measure flow in the anastomoses, detect any ischemic lesions, and evaluate exclusion of the aneurysm. Three months after treatment, all patients were re-evaluated. Clinical and neurological examination and the modified Rankin Scale score [16] (mRS) were recorded. Late postoperative (> 3 months) MR imaging was performed in each patient to detect any ischemic lesions and to evaluate cerebral perfusion. A late conventional angiography was performed after 1 year, to evaluate aneurysm occlusion and patency of the bypasses. Cranial Doppler was performed in each patient 3 months later to evaluate flow in the anastomoses.

Results

Population

The pre- and postoperative clinical characteristics and the angiographic results of the patients are presented in Table 1. The duration mean follow-up was 16 months (range 6 to 36).

Unruptured aneurysms were noted in six patients and ruptured aneurysm in four patients.

Concerning patients with unruptured aneurysm, symptoms were seizure in one patient, chronic headache in three patients, and diplopy in two patients.

The WFNS score was 1 in 2 patients and 2 in 2 patients.

Aneurysms characteristics

The location of aneurysm was on intracavernous ICA in three patients, on the supracavernous ICA in two patients, on M1 segment in two patients and on the MCA bifurcation in three patients.

The mean aneurysm diameter was 22 mm (range 16 to 35).

Calcifications were present on the aneurysm neck in six patients, and intrasaccular thrombus was noted in eight patients.

Microsurgical procedure

The mean time of microsurgical procedure was 11 h (range 9 to 12).

Previous STA MCA (M3 or M4 segment) anastomosis was performed in all patients. In seven patients, one STA-MCA anastomosis was made, and in three patients, a double STA-MCA anastomosis was performed because of good anatomical conditions (multiple branches of STA and good diameter of the recipient arteries) and M2-M2 side to side anastomosis was considered (in two patients among the three). Intraoperative indocyanine green videoangiography demonstrated the patency of this anastomosis in all patients during the procedure. Mean occlusion time of the recipient artery (M3 or M4 segment) occlusion was 42 min (30 to 70 min).

In all patients, the high-flow bypass was patent intraoperatively. Mean temporary occlusion time of the recipient artery (M1 or M2 segment) was 51 min (range 37 to 65 min). Occlusion of the parent artery during the microsurgical procedure was performed in seven patients (Fig. 2a, b). Surgical ligation on the cervical portion of ICA was performed in one patient with supracavernous ICA aneurysm; trapping a supracavernous ICA aneurysm by clipping distal ICA supracavernous segment, proximal ACA segment, and proximal M1 segment was performed in one patient; clipping only distal M1 segment before aneurysm neck was performed in one patient with MCA bifurcation aneurysm; trapping M1 aneurysm was performed in two patients with M1 aneurysm; and trapping by clipping distal M1 segment, proximal portion of the two M2 segments after creation of M2 to M2 side to side anastomosis was performed in two patients with MCA bifurcation aneurysm. Three patients underwent endovascular occlusion of the parent artery within the first 24 h after surgery.

Early post-procedural morbidity

Out of ten patients, one patient died from a large hemispheric infarction related to a common carotid artery dissection 10 days after the microsurgical procedure. No ischemic lesions were identified on early MRI before this fatal complication. Immediate postoperative epidural hematoma was noted in one patient, requiring surgical evacuation. Clinical recovery was slow, but favorable, with a mRS score of 3 by the end of hospitalization. There were no complications regarding wound healing or infection.

Fig. 2 A complex ICA aneurysm previously treated by endovascular coiling (**a**) was microsurgically excluded after performing a prior protective STA-MCA anastomosis followed by EC-IC high-flow bypass (**b**)
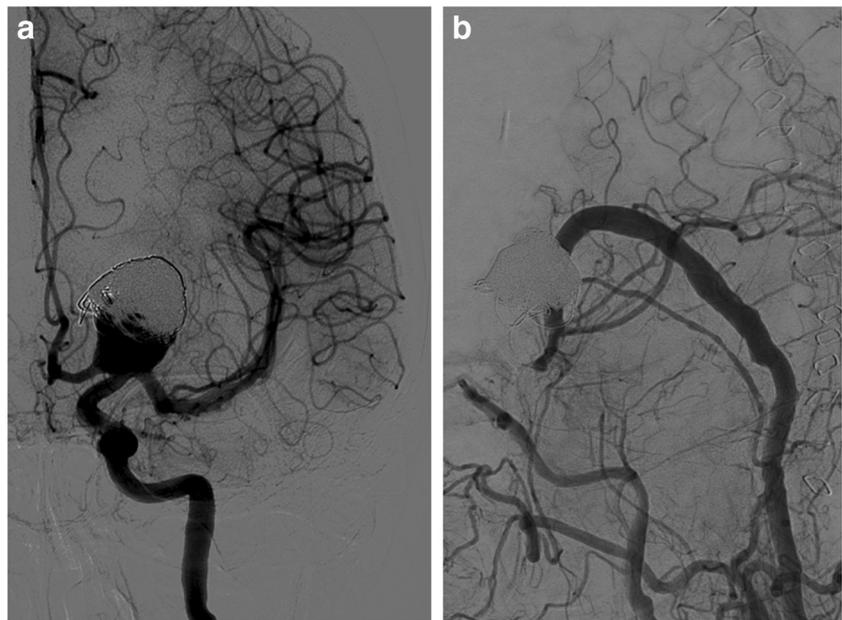
Radiological outcome

Complete occlusion of aneurysm was obtained in all patients. Early (< 7 days) occlusion of the ECA-MCA bypass, but not the STA-MCA bypass, was noted in one asymptomatic patient. No ischemic lesions were noted on early MRI in all patients. No aneurysm recanalizations and no delayed bypass occlusion were recorded during the follow-up.

Discussion

Morbidity of STA MCA bypass

STA MCA bypass is a valuable microsurgical procedure with demonstrated effectiveness in selected intracranial vascular diseases: MoyaMoya disease (MMD), aneurysm, skull base tumor [5, 13, 18]. The STA MCA bypass is usually known as a "low-flow" bypass but a "high-flow" bypass in this vascular anastomosis has been sometimes reported by some authors [4, 5]. However, this technique is usually associated with low morbidity [7]. Moreover, the patency rate is reported to be around 95% immediately after the bypass procedure [3, 6]. In a series of 264 MMD patients with 450 revascularization procedures, Guzman [7] reported that the surgical morbidity rate was 3.5% and the mortality rate was 0.7% per treated hemisphere after STA-MCA bypass. Complications were mainly related to the physiopathology of MMD, e.g., fragile vessels and unstable hemodynamics. It is likely that patients with MMD differ from our patient population with aneurysmal lesions without MMD. The quality of cortical vessels is considered higher in the latter group. Surgical morbidity of STA-MCA bypass should be even lower in this patient population. Moreover, MMD is involving extracranial artery as STA according to some authors [21]. Therefore, the risk of bypass thrombosis appears higher in MMD patients. In our study, STA MCA bypass was performed at the beginning of surgical procedure before the high-flow bypass in order to maintain distal MCA territory perfusion during vascular high-flow anastomosis with transient M2 segment clamping. The patency rate of STA-MCA bypass in our study was 100%, and there were no wound healing complications.

Morbidity of high-flow bypass

High-flow EC-IC bypass is an effective microsurgical treatment in patients with a giant/complex aneurysm located on anterior cerebral circulation [17]. This microsurgical procedure is associated with higher morbidity compared to STA-MCA bypass, partly due to the transient recipient artery clamping (M2 or M3 segments of MCA) [19]. The morbidity and mortality rates are close to 7% and 2%, respectively according to many authors [1, 18]. In a series of 29 patients with giant aneurysm managed by high-flow EC-IC bypass, Jafar [9] reported one death from a large cerebral infarction, neurological disorder related to ischemic lesion in two patients, and graft occlusion in two patients. In a series of 170 patients who underwent high-flow bypass, Sia [19] reported 14.7% of graft complications but leading to a mRS score > 2 only in 5.9% of cases. The mortality rate was 4% with a majority of thrombosed graft. Postoperative distal ischemia was noted in four patients (2.3%). In our series, we noted one death from a large infarction related to a common carotid artery dissection 10 days after the microsurgical procedure. It might be due to the occurrence of an intimal flap during the external carotid artery-vein graft anastomosis procedure that propagated.

There are some neuroprotective interventions [14] to limit the extent of cerebral ischemia during the temporary clipping of the parent artery, e.g., mild hypothermia, burst suppression, Sendai cocktail [22] (Manitol, Phenhydan, Solumedrol, Tokoferol; Cerebrolysin; fraction of inspired oxygen (FiO2) = 1, middle arterial pressure (MAP) = 100 mmHg, total intravenous anesthesia). Temporary clipping time plays without doubt a significant role in ischemic lesions occurrence. High-flow non-occlusive bypass using ELANA (excimer laser-assisted non-occlusive anastomosis) technique is also an effective therapeutic option in patient with giant/complex aneurysm [26]. However, morbidity and mortality are comparable to those of conventional high-flow revascularization operations [24] and also the rate of perioperative ischemic lesions is comparable between both these therapeutic options. In the study including 33 patients with giant aneurysm treated by ELANA technique, van Doormaal [25] reported 2 deaths (6%) and a nonfatal complication in 7 patients (21%). In the long term, 25 patients (74%) had a favorable outcome and 27 patients (79%) were independent (modified Rankin scale, < 3). In a study of 58 ELANA procedures for anterior and posterior circulation aneurysms in 64 patients, Vajkoczy [24] reported a perioperative mortality rate of 6% and 50%, respectively. At the 3-month follow-up, the mortality rate was 12% and 63% of the respectively. Further studies are required to confirm the supremacy of this non-occlusive procedure.

Combined treatment: STA-MCA bypass then high-flow bypass

The STA MCA bypass is generally regarded as a low-flow bypass, but it has been observed to evolve into a high-flow state over time. For example, some authors have reported safe ICA or MCA occlusion after STA MCA bypass [4, 5]. As the STA-MCA bypass procedure generally harbors low morbidity, we deemed it useful to perform this bypass as a protective measure, prior to performing a more risky high-flow EC-IC bypass. In this study, the main goal of performing the STA-MCA bypass was to maintain flow in the distal segments of the MCA during temporary clamping when performing the high-flow bypass, thus limiting perfusion deficits in distal MCA territory. This allowed us to extend temporary occlusion times for performing proximal MCA anastomosis. The mean time-clamping time was 51 min. No postoperative ischemic lesions in the MCA territory were detected on MRI. An additional benefit of performing a protective STA-MCA bypass prior to the high-flow one might be that one ends up with two patent bypasses after a successful procedure, compared to one bypass as is usually the case after the standard high-flow bypass procedure [8, 15]. In our study, early (< 7 days) occlusion of the ECA-MCA bypass, but not the STA-MCA bypass, was noted in one asymptomatic patient without ischemic lesions on MRI. A presumable downside of performing two bypasses—instead of one—in the same microsurgical procedure is that it increases total operating time. The risk of

anesthesia-related complications may possibly be higher because of this increased duration [10, 27]. On the other hand, creation of two bypasses might ultimately reduce the flow in each bypass and, consequently, increase the likelihood of bypass occlusion. Bypasses that remain patent typically maintain high flow rates. If the STA-MCA bypass provides ample flow to the MCA circulation, then the long-vein bypass is likely to occlude (especially so when flow rates become <40 mL/min). Contrarily, if the long-vein bypass carries significant flow, then the STA-MCA bypass is likely to involute due to lack of demand. Long-term evaluation of bypasses patency is required to evaluate the bypass occlusion when multiple bypasses were performed.

Limitations

Our study included a limited number of patients, a direct result of the rarity of the treated pathology. Ideally, a randomized controlled trial comparing outcomes of patients undergoing a single high-flow bypass procedure versus combined protective bypass and high-flow bypass should be performed to determine any additional benefit of a prior STA-MCA bypass. Moreover, we have not sufficient data from our two institutions related to the morbidity/mortality of high-flow bypass with a long-vein graft without protective STA-MCA bypass. These data would have been necessary in order to demonstrate a "need" for the protective bypass advocated for in this series. Nevertheless, valuable scientific and clinical progress can be made from observations in a relatively small group of patients. We did not also prove that STA-MCA anastomosis was not sufficient alone for flow replacement of the MCA segment in patients with MCA aneurysm. In those patients since the territory that is needed to be replaced include only the MCA, not the ACA, thus the total amount of blood flow that is needed for replacement tend to be much lower. More investigations with intraoperative flow measurements can be performed to determine the best surgical bypass strategy. Moreover, we can perform intraoperative test occlusion with electrophysiological monitoring to better understand the collateral blood flow and endogenous ischemic tolerance and to identify the subgroup of patients that will not tolerate temporary M2 occlusion. After these intraoperative tests, we have more data to decide if STA-MCA protective bypass at the beginning of the procedure is required.

Conclusion

In this study, we described the use of a protective STA-MCA bypass, performed prior to the high-flow bypass, in order to reduce the risk of perioperative ischemic lesions without increasing the morbidity of the surgical procedure. This treatment paradigm was feasible in all ten patients without complications related to the STA-MCA anastomosis. The rate of ischemic complication was 10% but probably not related to

the technique. As high-flow EC-IC bypass procedures are associated with significant morbidity due to the high rate of occurrence of perioperative ischemic lesions, any technique to limit cerebral ischemia is of potential value. We propose further evaluation of this protective low-flow bypass in clinical setting including randomized controlled trials.

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 (Lille University Hospital/ Ethic 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.

References

1. Bulsara KR, Patel T, Fukushima T (2008) Cerebral bypass surgery for skull base lesions: technical notes incorporating lessons learned over two decades. Neurosurg Focus 24:E11

2. Cantore G, Santoro A, Guidetti G, Delfinis CP, Colonnese C, Passacantilli E (2008) Surgical treatment of giant intracranial aneurysms: current viewpoint. Neurosurgery 63:279–289 discussion 289-290

3. Charbel FT, Meglio G, Amin-Hanjani S (2005) Superficial temporal artery-to-middle cerebral artery bypass. Neurosurgery 56:186–190 discussion 186-190

4. Cherian J, Srinivasan V, Kan P, Duckworth EAM (2018) Double-barrel superficial temporal artery-middle cerebral artery bypass: can it be considered "high-flow?". Oper Neurosurg (Hagerstown) 14: 288–294

5. Garrett MC, Komotar RJ, Starke RM, Merkow MB, Otten ML, Sciacca RR, Connolly ES (2009) The efficacy of direct extracranial-intracranial bypass in the treatment of symptomatic hemodynamic failure secondary to athero-occlusive disease: a systematic review. Clin Neurol Neurosurg 111:319–326

6. Gross BA, Du R (2012) STA-MCA bypass. Acta Neurochir 154: 1463–1467

7. Guzman R, Lee M, Achrol A, Bell-Stephens T, Kelly M, Do HM, Marks MP, Steinberg GK (2009) Clinical outcome after 450 revascularization procedures for moyamoya disease. Clinical article. J Neurosurg 111:927–935

8. Ishikawa T, Montello DR (2006) Spatial knowledge acquisition from direct experience in the environment: individual differences in the development of metric knowledge and the integration of separately learned places. Cogn Psychol 52:93–129

9. Jafar JJ, Russell SM, Woo HH (2002) Treatment of giant intracranial aneurysms with saphenous vein extracranial-to-intracranial bypass grafting: indications, operative technique, and results in 29 patients. Neurosurgery 51:138–144 discussion 144-136

10. Kim BD, Ver Halen JP, Grant DW, Kim JY (2014) Anesthesia duration as an independent risk factor for postoperative complications in free flap surgery: a review of 1,305 surgical cases. J Reconstr Microsurg 30:217–226

11. Lagares A, Alen JF, Gomez PA, Lobato RD (2005) Grading of subarachnoid hemorrhage: modification of the World Federation of Neurosurgical Societies scale on the basis of data for a large series of patients. Neurosurgery 56:E873 author replyy E873

12. Lawton MT, Quinones-Hinojosa A, Sanai N, Malek JY, Dowd CF (2003) Combined microsurgical and endovascular management of complex intracranial aneurysms. Neurosurgery 52:263–274 discussion 274-265

13. Low SW, Teo K, Lwin S, Yeo LL, Paliwal PR, Ahmad A, Sinha AK, Teoh HL, Wong LY, Chong VF, Seet RC, Chan BP, Yeo TT, Chou N, Sharma VK (2015) Improvement in cerebral hemodynamic parameters and outcomes after superficial temporal artery-middle cerebral artery bypass in patients with severe stenoocclusive disease of the intracranial internal carotid or middle cerebral arteries. J Neurosurg 123:662–669

14. Mracek J, Holeckova I, Lavicka P, Mork J, Stepanek D, Struncova P, Cerveny V (2011) The impact of neuroprotection on brain metabolism during carotid endarterectomy. Cas Lek Cesk 150:489–493

15. Ono H, Inoue T, Tanishima T, Tamura A, Saito I, Saito N (2018) High-flow bypass with radial artery graft followed by internal carotid artery ligation for large or giant aneurysms of cavernous or cervical portion: clinical results and cognitive performance. Neurosurg Rev 41:655–665

16. Rankin J (1957) Cerebral vascular accidents in patients over the age of 60. II. Prognosis. Scott Med J 2:200–215

17. Sanai N, Zador Z, Lawton MT (2009) Bypass surgery for complex brain aneurysms: an assessment of intracranial-intracranial bypass. Neurosurgery 65:670–683 discussion 683

18. Sekhar LN, Natarajan SK, Ellenbogen RG, Ghodke B (2008) Cerebral revascularization for ischemia, aneurysms, and cranial base tumors. Neurosurgery 62:1373–1408 discussion 1408-1310

19. Sia SF, Lai L, Morgan MK (2013) Measuring competence development for performing high flow extracranial-to-intracranial bypass. J Clin Neurosci 20:1083–1088

20. Sidi A, Lobato EB, Cohen JA (2000) The American Society of Anesthesiologists' physical status: category V revisited. J Clin Anesth 12:328–334

21. Sun SJ, Zhang JJ, Li ZW, Xiong ZW, Wu XL, Wang S, Shu K, Chen JC (2016) Histopathological features of middle cerebral artery and superficial temporal artery from patients with moyamoya disease and enlightenments on clinical treatment. J Huazhong Univ Sci Technolog Med Sci 36:871–875

22. Takahashi A, Suzuki J, Sugawara T, Yoshimoto T (1986) Surgical treatment of AVMs occluding these feeders during removal–utilizing the intraoperative balloon catheter and brain protective substances ("Sendai cocktail"). No shinkei geka Neurol Surg 14: 179–187

23. Tayebi Meybodi A, Huang W, Benet A, Kola O, Lawton MT (2017) Bypass surgery for complex middle cerebral artery aneurysms: an algorithmic approach to revascularization. J Neurosurg 127:463–479

24. Vajkoczy P, Korja M, Czabanka M, Schneider UC, Reinert M, Lehecka M, Schmiedek P, Hernesniemi J, Kivipelto L (2012) Experience in using the excimer laser-assisted nonocclusive anastomosis nonocclusive bypass technique for high-flow revascularization: Mannheim-Helsinki series of 64 patients. Neurosurgery 70: 49–54 discussion 54-45

25. van Doormaal TP, van der Zwan A, Verweij BH, Langer DJ, Tulleken CA (2006) Treatment of giant and large internal carotid artery aneurysms with a high-flow replacement bypass using the

excimer laser-assisted nonocclusive anastomosis technique. Neurosurgery 59:ONS328–ONS334 discussion ONS334-325

26. van Doormaal TP, van der Zwan A, Verweij BH, Regli L, Tulleken CA (2010) Giant aneurysm clipping under protection of an excimer laser-assisted non-occlusive anastomosis bypass. Neurosurgery 66: 439–447 discussion 447

27. Wong AK, Joanna Nguyen T, Peric M, Shahabi A, Vidar EN, Hwang BH, Niknam Leilabadi S, Chan LS, Urata MM (2015) Analysis of risk factors associated with microvascular free flap failure using a multi-institutional database. Microsurgery 35:6–12

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