Round table: Giant intracranial aneurysms

Giant and complex aneurysms treatment with preservation of flow via bypass technique

Traitement des anévrismes géants et complexes avec préservation du flux par technique de pontage

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ABSTRACT

Due to their anatomical characteristics and the complexity of the procedures required to obtain their complete occlusion, the treatment of giant intracranial aneurysms is a real challenge. Direct reconstructive strategies, whether by interventional neuroradiology (coils, stents) or microsurgical (clipping) means, are not always applicable and, in patients that would not tolerate parent or collateral artery sacrifice, the adjunction of a revascularization procedure using a bypass technique might be necessary. Cerebral arterial bypasses can be classified according to their function (3 types: flow replacement, flow reversal or protective), the branching mode of the graft used (3 types: pedicled, interpositional or in situ), the sites of anastomosis (2 types: extracranial-intracranial or intracranial-intracranial) and the class of flow they are supposed to provide (3 types: low-, intermediate- or high-flow). In this article, the authors review the different aspects in the management of patients with a giant intracranial aneurysm using a bypass: preoperative work-up, types of bypass and indications, surgical techniques and results.

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RÉSUMÉ
En raison de leurs caractéristiques anatomiques et de la complexité des procédures requises pour obtenir leur occlusion complète, le traitement des anévrismes géants intracrânien est un réel défi. Les stratégies de reconstruction directe, par des moyens endovasculaires (coils, stents) ou microchirurgicaux (clippage), ne sont pas toujours applicables et, chez les patients, ne pouvant tolérer le sacrifice de l’artère porteur ou de ses collatérales, l’adjonction d’une procédure de revascularisation utilisant une technique de pontage peut s’avérer nécessaire. Les pontages artérielles cérébraux peuvent être classifiés selon leur fonction (3 types : remplacement de flux, réversion de flux ou de protection), le mode de branchement du greffon utilisé (3 types : pédiculé, interposé ou in situ), les sites d’anastomoses (2 types : extracrânien-intracrânien ou intracrânien-intracrânien) et enfin la classe de débit qu’ils sont supposés fournir (3 types : bas débit, débit intermédiaire ou haut débit). Dans cet article, les auteurs font la revue des différents aspects de la prise en charge avec l’aide d’un pontage des patients porteurs d’anévrismes géants intracrânien : bilan préopératoire, types de pontages et indications, technique chirurgicale et résultats.

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1. Introduction

Because of their anatomical characteristics and of the complexity of the procedures required to obtain their complete occlusion, the treatment of a giant intracranial aneurysm (GIA) is a real challenge either for interventional neuroradiologists or neurosurgeons, with respective morbidity-mortality rates oscillating around 15–25% for anterior circulation aneurysms and 40–75% for posterior circulation aneurysms [1–6]. Nevertheless, treatment difficulties and risks are largely counterbalanced by the dismal clinical course of the disease after the onset of symptoms since cumulated 5-years follow-up morbi-mortality can reach 80% as a result of hemorrhage, ischemia (embolic events or perforator thrombosis) or mass effect [7,8]. This is explained to a great extent by a very high risk of spontaneous rupture at 5-year follow-up as shown in the results of the ISUIA trial [2]: 6.4%, 40% and 50%, respectively for intracavernous internal carotid artery (ICA), anterior circulation and posterior circulation aneurysms. Direct reconstructive strategies, whether by interventional neuroradiology (coiling, stenting) or microsurgical (clipping) means, are not always applicable and in patients that would not tolerate parent artery sacrifice, usually documented after balloon test occlusion, the adjunction of a revascularization procedure using a bypass technique might be necessary in order to minimize the risk of postoperative cerebral ischemia [9]. Furthermore, bypass procedures can render unclippable aneurysms clippable by supplying blood flow to collateral arterial branches that could not otherwise be preserved.

The first attempts of bypasses from extracranial to intracranial arteries, namely from the common carotid artery (CCA) to the intracranial ICA or the middle cerebral artery (MCA), were described by Worringer and Kunlin [10] and Lougheed et al. [11] respectively in 1963 and then in 1971. In 1969, Yasargil described the first superficial temporal artery (STA) to MCA intracranial-intracranial (EC-IC) bypass for the treatment of a complex aneurysm that required the ligation of the MCA [12]. Since then and until recently, several authors have described their results in the management of GIA with the use of such techniques [5,9,13–23]. In an effort to reduce the risk of postoperative ischemia due to the temporary cross-clamping of the recipient intracranial artery, nonocclusive anastomosis techniques have also been added to the treatment armamentarium (i.e.: ELANA technique [24–28].

In this article, the authors review the different aspects in the management of patients with a GIA for whom a bypass has already been selected as the treatment option: preoperative work-up, types of bypass and indications, surgical techniques and results.

2. Preoperative radiological work-up

2.1. Computerized tomography angiography (CTA)

CTA is useful to understand the 3D architecture of the Willis polygon and particularly the collateral pathways to the distal vascular bed of a parent artery carrying an aneurysm: posterior communicating artery (PcomA) and anterior communicating artery (AcomA). CTA also provides useful details about the aneurysm content (circulating and thrombosed portions) and should always be used to detect calcifications, which are the indicator of a thick and rigid wall, often atheromatous, that will preclude direct aneurysm reconstruction by clipping, even after aneurysm deflation by proximal clamping, puncture or endoaneurysmorraphy (Fig. 1). CTA is also interesting to understand the relationship of the aneurysm with the bony structures at the skull base: anterior and posterior clinoid processes, optic strut and cavernous sinus, jugular foramen and posterior aspect of the petrous bone.

2.2. Magnetic resonance imaging (MRI)

MRI and magnetic resonance angiography (MRA) are the most accurate means to analyze the aneurysm size and content, although they are not able to demonstrate aneurysmal wall calcifications. The filling part of the aneurysm will be shown on MRA (Fig. 1). This technique is also informative in the analysis the angioarchitecture of the Willis polygon (Fig. 1). Gradient echo sequence is used to look for previous asymptomatic perianeurysmal or intramural hemorrhage (Fig. 1). T2 or FLAIR sequence will also be useful to depict the aneurysmal wall thickness and detect the presence of an intrasaccular thrombus. In addition, MRI flow measurements can be interesting in the preoperative estimation of the flow to be replaced by the bypass (Quantitative MRI) [22].

2.3. Three-dimensional digital subtraction angiography (3D-DSA)

3D-DSA remains the gold standard for the analysis of the intraluminal angioarchitecture of the aneurysm and its collateral arteries (main trunk and branches of bifurcation). Reconstructions can be used to understand the 3D anatomy of the aneurysm by allowing multiple angles of view around the aneurysm volume (Fig. 1). This technique is also very precise to depict the relationship of the neck and sac with the surrounding perforating arteries, which is of paramount importance while considering the surgical treatment of these types of vascular lesions. To a certain extent, conventional DSA will also enable to visualize the anatomy of the
collateralization of the Willis polygon and the different arteries feeding the aneurysm.

2.4. Contrast enhanced transcranial Doppler (CE-TCD)

CE-TCD could also be used to demonstrate flow dynamics into the aneurysmal sac and its main collateral arteries. It is also interesting to analyze the structure of the aneurysmal wall and content: intraluminal thrombus, wall calcifications. For the planning of an EC-IC bypass, CE-TCD and peripheral conventional Doppler are important to study and select the appropriate donor vessel (STA on the aneurysm side, radial arteries or saphenous veins) according to the following characteristics: length, diameter and wall quality (patency, absence of varicosity or atheroma). If a radial graft is preselected, it is mandatory to perform an Allen test with Doppler ultrasound in order to confirm the presence of an adequate ulnar artery and a competent palmar arch that will insure hand perfusion after radial artery harvesting.

2.5. Exploration of cervico-encephalic arteries

CTA, MRA, DSA and cervical Doppler techniques might be combined to assess the quality of the extracranial segment of the cervico-encephalic arteries that will represent the potential routes of blood flow to the brain through the EC-IC bypass. If a proximal cervical anastomosis is required for an interposed graft, it will also be important to check the quality of the recipient artery, usually the ECA or one of its collaterals. Furthermore, it will be timesaving to locate preoperatively the level of the common carotid artery (CCA) bifurcation and ECA/ICA origins regarding the cervical spine levels.

2.6. Balloon test occlusion

The application of an occlusion testing before the treatment of a GIA with a bypass is a matter of debate in the cerebrovascular surgeon’s community. Some groups support a universal approach, whereby revascularization is routinely performed on all cases requiring vessel sacrifice while others advocate a selective approach, whereby a balloon test occlusion (BTO) guides the indications for surgical revascularization [20].

A BTO [5,9,15,20,24,29–31] performed in the awake patient is needed to assess the clinical tolerance to the Hunterian sacrifice of the parent artery carrying a GIA (Fig. 2), which could be one of the safest treatment options of this vascular condition. A balloon-catheter is driven up to the parent artery and inflated as proximally and closely as possible to the aneurysmal neck in order to exclude the collateral supply from the ECA (i.e.: ophthalmic artery). Direct clinical tolerance to parent artery occlusion is evaluated over time at 5, 10, 20, 30 minutes. The patient’s clinical intolerance to occlusion is confirmed by the occurrence of a neurological deficit, severe headaches, dizziness or consciousness disturbance during balloon inflation. In patients remaining asymptomatic, it is advised to apply a hypotensive challenge during vessel occlusion (lowering mean arterial blood pressure of 20 mmHg or 25%) in order to optimize the sensitivity of the test. Analyzing the venous phase delay between the tested and imaged vascular territories will primarily assess the hemodynamic tolerance (Fig. 3). This delay is considered minimal.
below 1 s, moderate between 1 and 2 s and significant above 2 s. Performing a transcranial Doppler or a PET scan could also help to assess the hemodynamic impact of vessel occlusion by measuring the velocities in the collateral arteries (i.e. MCA) or cerebral blood flow in the tested hemisphere in comparison with the contralateral one. A venous delay above 2 s and the reduction in the velocities (>20 cm/s or 30%) or brain perfusion of more than 30% will expose the patient to a high risk of future stroke if the tested artery is eventually sacrificed. When permanent sacrifice of the dominant vertebral artery (VA) is being considered, a 15-minute selective occlusion test is performed with neurological assessment and analysis of concurrent contralateral vertebral angiography to evaluate if the collateral flow from the other VA or PcomA is sufficient to support the posterior circulation and the contralateral posterior-inferior cerebellar artery (PICA).

Clinical and/or severe hemodynamic intolerance (negative test) is shown during BTO in approximately 20 to 30% of patients. In this situation (Fig. 3), and if reconstructive techniques (clipping, coiling, stenting) appear technically unfeasible pre- or peroperatively, Hunterian parent artery ligation (or prolonged temporary vessel occlusion) should be applied solely under the protection of a bypass (deconstructive technique). Its goal is to maintain appropriate flow in the distal vascular bed thus reducing the risk of postoperative stroke. Drawbacks of BTO are its associated morbidity (1.5% to 7%) due to dissections, emboli or pseudoaneurysm, with lower complication rates being described in the most recent reports [9]. The rate of falsely positive result, leading to unexpected secondary ischemic stroke, is about 2%, even if the BTO associates clinical testing, hemodynamic or EEG testing and hypotensive challenge.

In addition to the valuable hemodynamic information, the BTO will also help to precisely understand the angioarchitecture of the collateral circulation of the circle of Willis or cortico-pial connections between the different cortical arteries. In this respect, an Allcock's test should be performed during BTO (Fig. 2f), namely the concurrent injection of the opposite arteries to the tested artery (i.e. VAs when the aneurysm is on the ICA and vice versa). It permits to reveal flow reversal through a functional PcomA with the filling of the aneurysm sac or of the studied vascular territory.

3. Classification of bypasses and indications
3.1. General classification

In the management of GIA, cerebral bypasses can be classified according to their function (3 types: flow replacement, flow reversal or protective), the branching mode of the graft used (3 types: pedicled, interpositional or in situ), the sites of anastomosis (2 types: EC-IC or IC-IC) and the class of flow they should provide [3 types: low-flow bypass (LFB), high-flow bypass (HFB) and intermediate-flow bypass (IFB)].

Bypasses are usually constructed in order to preserve or replace the flow of the artery carrying the aneurysm and that needs to be sacrificed in order to exclude the aneurysm (flow replacement bypass). In some GIA, it is sometimes not possible to completely trap the aneurysm because of the presence of important perforators originating from or very close to the aneurysm sac and that needs to be kept patent. In this particular case of only proximal occlusion of the aneurysm, the bypass will supply the distal vascular bed but will also induce a flow reversal into the aneurysm, which might eventually favor aneurysmal thrombosis, involution or stabilization thus avoiding delayed rupture, and maintain perfusion in the perforators located closely to the aneurysm [15]. In the case when perforators emanate more proximally from the aneurysm, the so-called distal occlusion of the aneurysm is an alternative. However, both strategies should only be proposed when no viable option is available since it constitutes an incomplete treatment and exposes the patient to complications such as (re-) rupture (7%) or thrombosis of perforators (7%) [1,9]. Some authors have also advocated the
application of protective temporary bypasses during the treatment of GIA if a reconstructive surgical treatment is feasible (preservation of the involved artery) but requires a long cross-clamping time [17,20,32]. These protective bypasses are performed at the beginning of the procedure to ensure preservation of blood flow in the distal territory during aneurysmal manipulation, thus reducing the risk of peroperative stroke. They can be sacrificed or kept opened at the end of surgery if the flow in the distal vascular bed is maintained or interrupted.

Bypasses are most frequently used to derive blood flow from one of the carotid arteries (common, internal or external) to the intracranial arteries (EC-IC bypasses), usually by means of an ECA distal branch [superficial temporal arterial or occipital artery (OA)] or an interposed graft (saphenous vein or radial artery). Intracranial-intracranial (IC-IC) bypasses have become more frequently used because of the improvement of microsurgical experience [15,20] but also due to the contribution of the ELANA technique. In the past, they did not have surgeons’ preference [9] because they are more complex, which put two vascular territories at risk for ischemia and require longer cross-clamping times. Indeed, the interposition of a graft between two cerebral arteries (i.e.: ICA and MCA, M1 and M2, M2 and ACA) or the side-to-side anastomosis between two cerebral arteries that are naturally close together (i.e.: pericallosal arteries, PICAs, M2 branches) is time consuming. Arterial transposition is another way to revascularize a branch that cannot be preserved during the exclusion of a GIA (Fig. 4). The origin of the
3.2. Low-flow EC-IC bypass

LFB uses arteries with a diameter of up to 2 mm that will insure a median cerebral blood flow around (30–50 cm²/min) although higher flows (> 80 cm²/min) could be obtained immediately or after a few days or weeks, depending on the calibre of the donor and recipient arteries [9,20–22]. They include the classical superficial temporal artery (STA)-MCA bypass, the OA-MCA or OA-PICA bypasses. Good patency rates (> 95% have been reported) [9,21]. Their indications are summarized on Fig. 3. This type of bypass is usually sufficient to insure appropriate blood supply to a distal cortical territory, for example: M2 branch of the MCA, ACA, PCA, PICA or sometimes, if large donor and recipient arteries are available, complete MCA flow. They can also be applied for the replacement of the ICA flow (Fig. 5), if there is good additional flow through the AcomA and/or PcomA and the BTO encounters perfect clinical tolerance, only moderate hemodynamic disturbances in the homolateral vascular territory and a venous phase delay < 2 s [9].

3.3. High-flow and intermediate-flow EC-IC bypasses

HFB will provide higher flow rates (> 50 cm³/min and often > 100–150 cm³/min) and therefore will be used for flow replacement of the entire ICA territory or the MCA vascular bed [5,9,16,20,21]. Their indications are summarized on Fig. 3. HFB is typically required when there is a need of sacrificing a large cerebral artery with documented clinical compromise (prior to or during provocative hypotension) or hemodynamic intolerance with venous phase delay > 2 s at the preoperative BTO [9]. These bypasses will employ larger donor and recipient vessels than LFB. The extracranial anastomosis will usually be performed at the neck and at the level of the proximal external carotid artery (ECA) to avoid cross-clamping the ICA during proximal suturing. The intracranial anastomosis will be implanted distally to the giant aneurysm at the supraclinoid ICA, M1 or M2 segments of the MCA. An interposed graft will be used and chosen depending on the surgeon’s preference, availability, quality, length, size of the recipient intracranial vessel and desired flow [20]. The saphenous vein is the most accessible graft but also has the inconvenience of its venous endothelium (risk of delayed fibrous intimal proliferation or atherosclerosis), its higher risk of kinking or mismatch due to its larger calibre (5 mm) and thickness. These characteristics may lead to turbulent or stagnant flow and secondary thrombosis [9]. This probably explains its lower early primary patency rate (85% at 1 month in aneurysm surgery) and delayed risk of stenosis or occlusion (late patency rate around 82% at 5-years and 73% at 13-years) [16]. Nevertheless, depending on the quality of the graft and of the extracranial and intracranial vessels, it is able to deliver very high-flow approximately 100–200 cm³/min [16,20,21]. The radial artery, with a diameter of 3.5 mm, could also be a very valuable graft, and can be harvested provided the Allen test finds a competent palmar arch. It will provide a flow of around 50–150 cm³/min [20,21]. This type of graft is associated with higher early and late patency rates in the treatment of internal carotid artery aneurysms: 95% at 3-weeks and at 5-years [17] which is comparable to the results obtained in coronary surgery (95% at 3-weeks and 92% at 5-years) [9,21]. Asymptomatic stenosis may be encountered at 5-years in 10% of...
the cases [17]. However, the radial artery is less easy to manipulate because of its retractile and spastic character [21]. Its length and diameter are also smaller than a saphenous vein thus potentially reducing respectively the feasibility of the bypass or the amount of flow that could be delivered to the brain. One way of solving the length issue with this type of graft is to tunnel it through a submandibular route [19] or to perform the proximal anastomosis on the main trunk of the STA just above the zygoma [9] or on the maxillary artery through a drilling at the level of the middle fossa [18], thus ending, in these latter cases, with an “intermediate” flow bypass (about 70 cm²/min), depending on the calibre of the donor trunk itself.

4. Surgical techniques and results

4.1. Anesthetic considerations

In patients undergoing bypass procedure, the anesthetic management aims at enhancing brain relaxation, optimizing cerebral protection against ischemia and maintaining appropriate perfusion in the bypassed territory, thus reducing the risk of perioperative complications [9,15,20]. Brain relaxation is obtained by surgical means (ventricular or lumbar catheter, opening of arachnoid cisterns or lamina terminals) but also by anesthetic measures (deep anesthesia, mannitol). It is also fundamental to maintain, perfect stability of arterial blood pressure from induction to extubation of the patient (corresponding to the patient’s usual range), usually monitored by an invasive method, and to avoid any severe hypo- or hypertension. In each case, during the temporary clipping of the cerebral recipient artery, the mean arterial blood pressure should be elevated to 10 mmHg or 20% from basal values using adrenergic agonists and barbiturate burst suppression (pentothal) should be induced in order to minimize the risk of secondary ischemia. Some authors use also adjunctive mild hypothermia (risks of coagulopathy and arrhythmia) and monitoring of sensory- or motor-evoked potentials in order to adapt and improve brain protection. Since, all these interventions will only prolong the time of ischemia-induced infarction and apoptosis, certain artery segments will still not tolerate long cross-clamping duration, either because of poor collateral supply (supraclinoid isolated ICAs) or because of the presence of the origin of critical perforators (ICA bifurcation, MCA-M1, PCA-P1, and the BA). Other vascular segments could tolerate longer temporary occlusion time from 15–20 minutes to 60 minutes without the occurrence of brain infarction, especially under burst suppression.

The treatment of these patients also involves the periprocedural management of antiagregant and anticoagulant treatments in order to reduce the risk of bypass thrombosis. Although there is no clear consensus, most of the surgical teams introduce an antiagregant treatment (acetylsalicylic acid 75 to 325 mg daily) 1 day or 1 week prior to surgery (except in the case of a ruptured GIA), and then 300 mg daily the first following week and then 75 mg daily for life. Heparin could be used at surgery (except if a ruptured GIA is not secured) and at the time of the temporary proximal occlusion of
the recipient cervical or intracranial vessel. A single moderate dose (2000 to 3000 units) of non-fractioned heparin can be delivered allowing spontaneous normalization of coagulation throughout the end of the procedure. This should be assessed before reintroducing the antiagregant treatment. We do not recommend the use of full anticoagulation or clopidogrel (i.e. in case of resistance to aspirin) because of the increased risk of postoperative intracranial hemorrhage [33].

4.2. Low-flow bypass

The surgical technique of LFB has been described in details in a previous article [34]. When methodically performed, the procedure itself is associated with a high rate of patency (>95%), low mortality and morbidity (about 1% and 4%, respectively) [9,21,22,35,36]. Postoperative complications in the treatment of GIA with LFB often result from aneurysm manipulation, perforators compromise or secondary bypass occlusion. This later complication could be avoided by measuring perioperatively the quality of bypass flow with a flowmeter. A cut flow index (ratio between bypass flow/cut flow) inferior to 0.5 appears to be a strong indicator of bypass dysfunction with high risk of secondary occlusion (50%) [22].

4.3. Conventional high-flow bypass

Since the first application of extracranial-intracranial bypasses for cerebral revascularization in the 1960’s [12], conventional micro-aneurysms remains the gold standard and implies a temporary occlusion of the recipient artery followed by termino-lateral suturing of the donor vessel [5,9]. If a saphenous graft is chosen, the vein is usually harvested retrogradely from the ankle to the knee in the subcutaneous fat of the leg, which offers a sufficient length to connect the cervical ECA to any of the intracranial arteries. The course of the vein from the medial malleolus to the knee could be marked preoperatively during a lower limb venous Doppler. The vein is dissected up to the adventitial layer and the collateral branches are ligated or clipped and then divided. Care is taken to mark the proximal end of the vein in order to correctly orientate the vessel and the valvulae according to the direction of the arterial flow (the vein is transposed cranially and flushed with heparinized saline to confirm the good direction of flow before anastomosis). Some authors advocate to perform a valvelucotomy to avoid any reduction of flow into the venous graft but this could lead to endothelial injury and secondary clot formation [37]. If a radial graft is selected (Fig. 6), the artery is usually harvested retrogradely from the wrist to the elbow, all along and then below the brachio-radialis muscle that will be retracted out with self-retainers. The artery is eventually exposed up to the adventitial layer and the collateral branches are ligated or clipped and then divided. The artery could be left in situ until final anastomosis. This graft usually offers a sufficient length to join the cervical ECA to any of the intracranial arteries, but the elastic and spastic character of the artery might induce a notable retraction and narrowing of the artery after it is sectioned. To avoid this inconvenience, some authors have proposed a pressure distension technique to maintain the appropriate calibre and length of the artery [20,21]. The graft is then flushed and stored in vasodilator (calcium channel blocker or sodium nitropusside) and heparin solution until anastomosis [9].

The patient is placed in a supine position the head fixed in a clamp and turned to the contralateral side of 45°, the neck slightly extended in order to correctly present the cervical region along the medial aspect of the sternocleidomastoid muscle. A large fronto-pterional craniotomy is performed (some authors add an orbito-zygomatic deposit) and the Sylvian fissure is widely opened in order to expose the anterior part of the circle of Willis. The intracranial part of the bypass is usually performed in first instance because it is easier to mobilize the graft and expose the back wall of the anastomosis while suturing if the other extremity is not attached, particularly if the intracranial site of connection is deeply located. A large cerebral branch is selected as a recipient vessel according to the site of the aneurysm and to preoperative digital subtraction angiography (DSA) to insure appropriate cerebral flow. Care should be taken to exclude perforating branches from the bypassed segment (i.e.: anterior choroidal artery, lenticulostriate arteries) because these terminal arteries have poor tolerance to the temporary occlusion needed for the micro-aneurysm (20 to 45 min on average depending on the location and size of the vessels). Monitoring of motor-evoked potentials (MEP) and somatosensory-evoked potentials (SEP) could be useful to detect any intolerance to the temporary occlusion of the recipient vessel [5]. The cerebral branch is isolated, and after barbiturate (thiopental sodium) induced burst suppression, temporary occluded while 2000 to 3000 UI of heparin can be delivered to the patient. An arteriometry (linear or elliptical) is performed and the attachment is made using 8 to 10 interrupted or 2 half-running sutures with 10.0 nylon or polypropylene depending on the thickness of the donor and recipient vessels walls. After having confirmed the good watertightness and patency of the anastomosis, the recipient artery is unclamped and the donor graft can be temporary clipped. In ICA aneurysm patients, the bypass can be performed directly on the distal ICA or on a large branch of the MCA (M1 or preferentially M2 that does not usually carry perforating branches). In MCA aneurysm patients, the bypass can be implanted on a large M2 or M3 branch. When the MCA bifurcation is involved by the aneurysms, the revascularization of both M2s could be performed whether by two donor vessels or with a barrel bypass using a single graft that is connected on both MCA branches by one end-to-side and one side-to-side anastomosis. In giant AcomA aneurysms, it is sometimes necessary to revascularize one of the two A2s. This can be done using a long venous graft connected intracranially on the pericallosal artery or by a side-to-side anastomosis between both pericallosal arteries, if one of the branches can be kept patent at its origin. In GIA of the posterior circulation involving the BA, it might be required to occlude both vertebral arteries in order to decrease the hemodynamic stress into the sac by reversing the flow into the BA. When the polygon is “fragile” (absence of efficient posterior communicating arteries), it might be necessary to augment the blood supply to the posterior circulation, before proximal occlusion of both VAs, by implanting a bypass on one of the PCA using a large and long STA, an interposed radial or a venous graft. The conventional approach is subtemporal and exposes the patient to significant brain retraction and to postoperative temporal lobe swelling, which could be avoided by a CSF depletion (lumbar drainage). The deep and narrow operative corridor available for suturing through this approach and the presence of perforating branches directed to the brain stem, that could not tolerate long cross-clamping times, represent the main drawbacks in this location [9]. Monitoring of MEP and SEP is advised in order to detect any intolerance to PCA temporary clamping. In giant aneurysms, involving a PICA origin, the artery could be revascularized whether by an OA-PICA bypass or by a side-to-side anastomosis between both PICAs if their calibre and proximity (“kissing-PICA”) are appropriate.

The extracranial part of the bypass is performed in second instance. A cervical incision is made along the anterior aspect of the sternocleidomastoid muscle at the level of the CCA bifurcation identified on preoperative imaging. Then the ECA and ICA initial segments are exposed. The graft can be tunnelled subcutaneously through a chest tube introduced from the lower part of the scalp incision in front of the zygoma to the cervical incision. The neck incision can also be extended to reach the scalp incision and the graft
Fig. 6. Treatment of a giant growing atheromatous and fusiform aneurysm of the left internal carotid artery (ICA) termination (limited collateral flow at balloon test occlusion) with a high-flow radial artery bypass and aneurysmal trapping (L. Thines): a: anterior view of the 3D reconstruction of rotational angiography of the left ICA; b: intraoperative view through a left peritalar approach showing the ICA aneurysm not amenable to direct clipping because of diffuse atheroma and calcifications; c: harvesting of the radial artery on the left forearm; d, d’: an interposed radial artery bypass (arrowhead) between the STA trunk (black arrow) and an middle cerebral artery-M3 branch (white arrow) was performed; e, e’: the aneurysm was trapped at the supraclinoid ICA (e), A1 and M1 (e’) with preservation of the anterior choroidal artery (white arrow) and lenticulostriate arteries origins (not shown); f: peroperative videoangiography confirming the patency of the bypass (arrowhead: anastomotic site); g: postoperative angiography (anterior view) of the left external carotid artery showing the patency of the bypass (arrowhead: anastomotic site; arrow: interposed radial artery graft).

Treatment of an aneurism géant fusiforme évolutif et athéromateux de la terminaison carotidienne gauche (collatéralité insuffisante au test d’occlusion par ballonnet) par un pontage haut débit radial et trapping anévrismal (L. Thines): a: vue antérieure de la reconstruction 3D de l’angiographie rotationnelle de l’artère carotide interne (ACI) gauche; b: vue opératoire par un abord peritalar gauche montrant un anévrisme non accessible à un clippage direct en raison d’importantes calcifications et d’un athérome diffus; c: prélèvement de l’artère radiale sur l’avant-bras gauche; d, d’: un pontage radial interposé (tête de flèche) entre le tronc de l’artère temporaire superficielle (flèche noire) et une branche M3 de l’artère cérébrale moyenne (ACM) (flèche blanche) était réalisé; e, e’: l’anévrisme était trappé au niveau de l’ACI supraclinoidienne (e), A1 et M1 (e’) avec préservation de l’origine de l’artère choroidienne antérieure (flèche blanche) et des artères lenticulostriées (non visibles); f: vidéo-angiographie peropératoire confirmant la perméabilité du pontage (tête de flèche: site d’anastomose); g: angiographie postopératoire (vue antérieure) de l’artère carotide externe gauche montrant la perméabilité du pontage (tête de flèche: site d’anastomose; flèche: greffon radial interposé).

can be eventually buried in the subcutaneous fat all along its course. This latter technique allows to obtain a strict hemostasis of subcutaneous vessels avoiding the risk of cervical hematoma with graft compression and to look for any twisting or narrowing of the donor vessel before closing the skin. The length of the graft should be sufficient to join both sites of connection without tension. A circular or elliptical arteriotomy is performed on the ECA origin and the graft is sutured using 7.0 or 8.0 nylon or polypropylene running or interrupted sutures (mean anastomosis time is about 25 minutes). Before the completion of suturing, the radial graft is unclamped allowing retrograde flushing at the site of cervical anastomosis. If a saphenous vein is used, back bleeding is usually not possible because of the valvulae and the vein has to be flushed with saline before the last intracranial stitch is tied and maintained filled thereafter [20]. Hemostatic materials can be applied at both anastomosis sites to improve water-tightness of the sutures.
Fig. 7. Traitement d’un anévrisme giant intracrânien de l’artère carotide interne gauche par un pontage hauteur débit veineux selon la technique Excimer laser-assistant nonocclusive anastomosis (ELANA) entre l’artère carotide externe et l’artère carotide interne (T. Thines, A van der Zwan): a. AMRM montrant un anévrisme giant intracrânien de l’artère carotide interne (tête de flèche); b : vue latérale de l’artériographie carotidienne gauche retrouvant une artère communicante postérieure de petit calibre (tête de flèche). À noter, la stase de flux au sein du sac anévrismal (flèche); c : test d’occlusion par ballonnet carotidien gauche montrant l’absence de collatéralité par l’artère communicante antérieure vers l’hémisphère gauche, d : sélection de la taille de l’anneau de platine et du site d’implantation du pontage, e : sutures de la veine saphène au tour de l’anneau de platine avec huit points séparés de nylon 8.0, f : après avoir été calibré, le cathéter laser est introduit dans le segment veineux jusqu’à appliquer fermement et perpendiculairement contre la paroi de l’artère receveuse. Puis l’inspiration d’un système de vide est mise en route pour 2 min, g : le laser est activé pendant 5 secondes pour réaliser l’artériotomie et un reflux est obtenu dans le greffon veineux, h : l’artériotomie est retrouvé au bout du cathéter ; i : le segment veineux extracrânien est anastomosé en termo-latéral à l’artère carotide externe (ECA) cervicale par 2 hémisurjets de nylon 8.0 (ICA : artère carotide interne), j : les extrémités des deux segments veineux sont réunis par 2 hémisurjets de nylon 8.0, k : mesure de débit avec un débitmètre (Flowmeter Transonic systems Inc® Ithaka, NY, États-Unis) afin de confirmer le pontage extra-intracrânien. © 2020 Elsevier Masson SAS. Tous droits réservés.
Indocyanine green videoangiography is a good technique to confirm the patency of the bypass intraoperatively but the flow evaluation is only semi-quantitative [38]. Precise measurement of the flow with a flowmeter is strongly advised to certify that the target flow is obtained before occluding the main artery containing the giant aneurysm. This assessment can also be performed postoperatively using quantitative MRA [22] or transcranial Doppler techniques. Intraoperative diagnosis of bypass dysfunction or failure should lead to bypass revision, although the success rate of this manoeuvre is low [15]. The question about the timing of occlusion of the main vessel remains debated. If an appropriate and strong flow is quickly observed through the bypass, many authors advocate proximal ligation or trapping of the diseased artery during the surgical procedure in order to avoid competitive flow at the anastomotic site or under-solicitation of the bypass leading to its secondary thrombosis [5]. If the bypass result looks uncertain or bypass flow is borderline, 48–72 hours might be necessary for the bypass to grow to a satisfying range of flow and to allow staged endovascular occlusion of the main artery without running the risk of secondary cerebral ischemia. Combined treatment could also be an option in some aneurysms with primary revascularization of a collateral branch and secondary coiling or stenting of the malformation [39]. Postoperatively the patient receives Aspirin® 75 mg daily.

4.4. Nonocclusive high-flow bypass (ELANA technique)

Conventional micro-anastomosis has several interests, among which its long-term durability and its adaptability to any location. One of the drawbacks in the treatment of GIA with this technique is the risk of ischemia related to the cross-clamping time needed for the construction of the bypass and particularly during the intracranial anastomosis. Indeed, it remains difficult to perform quickly a bypass in proximal locations (i.e.: supraclinoid ICA, M1 segment, P1 segment) because of the narrowness of the surgical corridor and the deepness of the suture site. A longer occlusion time is needed and associated with a higher risk of perioperative stroke [40] since interruption of blood flow over 10 min in a main cerebral artery is associated with an ischemic risk of 45%. As pharmacological protection would only reduce this risk of 10–20% [41], the conventional technique remains problematic in patients selected for flow replacement bypasses precisely because of intolerance to proximal occlusion. This has led the Utrecht group (Prof. Tulleken, Prof. van der Zwan) to develop a new technique allowing to perform the procedure without any temporary occlusion of the cerebral recipient artery [42]: ELANA technique.

The favourite graft for this technique is a saphenous vein harvested at the lower limb and then divided in two half segments that will then be oriented according to the valvulae (Fig. 7). The distal “intracranial” segment of the vein is passed through a platinum ring (two sizes available 2.6 and 2.8), everted over the ring and then sutured on the ring with eight 8.0 prolene interrupted sutures outside the operative field. The distal end of the vein and the ring are then attached termino-laterally to the intracranial artery with eight 8.0 prolene interrupted sutures (4 transfixing and 4 superficial). It is recommended to check that the connection between the recipient and donor vessels does not leak by flushing the graft with saline solution with pressure equivalent to systolic blood pressure. The arteriotomy is performed nonocclusively with the ELANA catheter 2.0 introduced in the “intracranial” segment of the vein until it firmly applies perpendicularly to the recipient artery wall. The suction of a vacuum system is activated for 2 minutes in the catheter that should stay perfectly steady, so that the recipient artery wall is pulled in perfect contact with the catheter tip. The laser is then activated for 5 seconds at 40 Hz and 10 mJ delivering a total of 200 pulses. The ELANA catheter is then carefully removed. Retrograde blood flow through the donor graft will confirm the successful penetration of the artery wall by the laser light delivered through the catheter and if necessary can be stopped by temporary occluding the donor graft until completion of the bypass. After

### Table 1

**Results of bypass surgery for giant intracranial aneurysms.**

<table>
<thead>
<tr>
<th>Series</th>
<th>Nb</th>
<th>Anterior circulation</th>
<th>Posterior circulation</th>
<th>Rate of RA</th>
<th>Nb BP</th>
<th>EC-IC/IC-IC HFB</th>
<th>LFB</th>
<th>Morbidity</th>
<th>Mortality</th>
<th>Patency</th>
<th>Occlusion</th>
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<tr>
<td>Lawton et al., 1996 [45]</td>
<td>63</td>
<td>86%</td>
<td>14%</td>
<td>na</td>
<td>63</td>
<td>75%/25%</td>
<td>44%/SVG 23 STA-SVG 5 100%/Rad 43</td>
<td>56%/STA 19 IS 3 PA 13</td>
<td>5%</td>
<td>2%</td>
<td>92%</td>
</tr>
<tr>
<td>Houkin et al., 1999 [17]</td>
<td>43</td>
<td>100% (ICA)</td>
<td>0%</td>
<td>0%</td>
<td>43</td>
<td>100%/0%</td>
<td>87%/SVG 38 Rad 41</td>
<td>13%/STA 3 IS 1 PA 8</td>
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<td>12%</td>
</tr>
<tr>
<td>Sekhar et al., 2008 [20]</td>
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<td>78%</td>
<td>–</td>
<td>na</td>
<td>91</td>
<td>90%/10%</td>
<td>100%/SVG 41</td>
<td>13%/STA 3 IS 1 PA 8</td>
<td>na</td>
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<tr>
<td>Cantore et al., 2008 [5]</td>
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<td>95%</td>
<td>5%</td>
<td>24%</td>
<td>41</td>
<td>100%/0%</td>
<td>100%/SVG 41</td>
<td>–</td>
<td>4.9%</td>
<td>9.8%</td>
<td>98%</td>
</tr>
<tr>
<td>Sanai et al., 2009 [15]</td>
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<td>68%</td>
<td>32%</td>
<td>26%</td>
<td>82</td>
<td>57%/41%</td>
<td>49%/SVG 30 Rad 10</td>
<td>51%/STA 15 OA 1 IS 9 PA 17</td>
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<td>Kalani et al., 2014 [31]</td>
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<td>63%</td>
<td>37%</td>
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<td>57</td>
<td>86%/14%</td>
<td>26%/SVG 1 Rad 14</td>
<td>74%/STA 30 OA 4 IS 14</td>
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<tr>
<td>van Doormaal et al., 2008 [25]</td>
<td>34</td>
<td>100% (ICA)</td>
<td>–</td>
<td>26%</td>
<td>40</td>
<td>100%/0%</td>
<td>100%/SVG ELANA</td>
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<tr>
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<td>100% (MCA)</td>
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<td>25</td>
<td>8%/92%</td>
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<td>18%</td>
<td>5%</td>
<td>80%</td>
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<tr>
<td>Vajkoczy et al., 2011 [24]</td>
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<td>86%</td>
<td>–</td>
<td>5%</td>
<td>52</td>
<td>83%/17%</td>
<td>100%/SVG ELANA</td>
<td>–</td>
<td>14%</td>
<td>12%</td>
<td>86%</td>
</tr>
</tbody>
</table>


having confirmed the water-tightness of the anastomosis and retrieved the arterial flap sucked at the catheter tip, 2,000 to 3,000 units of heparin are then delivered to the patient. In the event that the arterial flow does not fill the graft or the disk of cut out tissue is not retrieved, the donor graft and the anastomosis site can be inspected from the inside through a linear incision of the donor graft close to its end and under very short temporary occlusion of the recipient artery.

As a proximal, extracranial anastomosis site for the extracranial segment of the donor vein, the ECA (Fig. 7) or a large STA trunk can be selected. This is performed in a conventional way because patients are able to tolerate a temporary occlusion of the ECA, with the exception of a small group of patients with an occluded ICA and effective retrograde opthalmic flow. Both donor graft segments are then connected end-to-end with conventional 8.0 sutures and before final closure, the temporary clips on the donor vessel segment can alternatively be released to allow flushing the graft and are finally removed. Indocyanine green videoangiography and flow measurement with a flowmeter are used to confirm intraoperatively the good patency and effectiveness of the bypass [43]. The surgeon can eventually proceed with the occlusion of the diseased artery containing the aneurysm.

5. Results

The natural history of giant intracranial aneurysms is poor, since it carries a high risk of rupture and morbi-mortality, and therefore, often justifies complex and aggressive curative strategies that are summarized on Fig. 3. SAH patients have worse outcomes with ruptured than unruptured giant aneurysms: in the first group 61% were improved or stable, 52% had good outcomes (GOS 4–5), and 39% died; in the second group, 82% were improved or stable, 84% had good outcomes, and 8% died [1]. According to the experience of high caseload centers, less than half of GIAs are amenable to direct clipping after surgical exploration [1]. The use of deep hypothermic circulatory arrest is only dedicated to particular cases because of its high combined rate of permanent morbi-mortality (32%) [44]. Hence, indirect treatment of unclippable GIA with bypass technique has progressively become a more acceptable alternative. The construction of a bypass prior to the surgical or even endovascular treatment of a GIA has also been shown to improve the functional prognosis and the survival of patients when no selective or reconstructive endovascular or surgical option is applicable [14]. Several series have been published showing the value of these procedures with conventional or ELANAS bypass techniques [5,15,17,20,24–26,31,45]. Table 1 summarizes the results obtained in the largest cohorts published to date.

6. Conclusion

First of all, during the selection of a patient for a revascularization procedure for the treatment of a GIA, it is necessary to determine which kind of bypass is more suitable (protective or replacement, low- or high-flow, conventional or nonocclusive) and which anastomotic sites will be chosen together with the type of donor graft. This decision-making process is made according to the feasibility of reconstruction of the main artery, the quantity of flow needed regarding the preoperative hemodynamic assessment (DSA, BTO, Quantitative MRI) and the size and quality of recipient and donor vessels. The nonocclusive ELANA technique offers a substantial possibility of performing the bypass without any occlusion time of the recipient cerebral artery. The results obtained with these techniques compares favourably with the poor natural history of GIAs, particularly for anterior circulation aneurysms.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

References


