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REVIEW

Bypass in neurosurgery—indications and techniques

L. Wessels[1] · N. Hecht[1] · P. Vajkoczy[1]

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Abstract
Since the introduction of cerebral bypass surgery by Professor Yasargil in 1967, a plethora of literature has been published on direct cerebral revascularization. Against this background, it is remarkable that at present, only three randomized controlled trials (RCTs) exist in the field, both dealing with extracranial to intracranial bypass surgery for flow augmentation in patients at risk to suffer ischemic or hemorrhagic stroke due to cerebrovascular disease. Next to flow augmentation, the other main indication for bypass surgery is to provide flow replacement following proximal vessel sacrifice for treatment of complex aneurysms or skull base tumors. The aim of this review was to provide a comprehensive overview of the literature regarding the indications and the techniques of cerebral bypass surgery for prevention of cerebral ischemia.

Keywords Chronic cerebral ischemia · Extra-intracranial bypass · Revascularisation · COSS · Complex cerbral aneurysm

Introduction

Surgical cerebral revascularization was first introduced by Professor Yasargil in 1967 [1] and during the past four decades, technical and technological advancements have considerably influenced the field [2]. Due to its high complexity and strict indication as well as the need for a highly specialized team of anesthesiologists, neurologists, neurointerventionalists, and neuro-intensive care specialists surrounding the surgeon, cerebral bypass procedures remain limited to a small number of highly specialized centers.

Conceptually, cerebral bypass surgery aims at augmentation or complete replacement of blood flow to the brain provided by one cerebral artery. On the one hand, cerebral bypass surgery for flow augmentation is a treatment option for patients with chronic cerebral ischemia. Despite hemodynamic rescue, however, the indication for bypass surgery for patients with arteriosclerotic cerebrovascular disease remains controversially discussed and so far, only patients with Moyamoya disease appear to have a clear benefit from extracranial to intracranial flow augmentation with the goal to prevent cerebral ischemia [3] and to reduce the risk for rebleeding in patients with hemorrhagic Moyamoya disease [4, 5]. On the other hand, bypass grafting for flow replacement is clearly needed in cases where complex vascular lesions (i.e., fusiform or dolichoectatic giant aneurysms) or skull base tumors require proximal vessel sacrifice to permit exclusion of the vascular lesion from the circulation or complete tumor resection.

Technically, a large armamentarium of bypass strategies has been developed and refined over the past decades, mainly subdivided into pedicle bypass grafts with transposition of an extracranial donor vessel (i.e., superficial temporal artery to middle cerebral artery = STA-MCA bypass) and non-pedicled arterial or venous interposition bypass grafts (i.e., radial artery or saphenous vein intermediate or high-flow bypass). Apart from these typically extra- to intracranial (EC-IC) bypass types, intracranial to intracranial (IC-IC) bypass grafts should be regarded separately as technically the most challenging cerebral bypass for selected cases that permit flow replacement through strictly intracranial CBF redistribution between vascular territories.

Bypass techniques

Techniques of cerebral revascularization depend on the individual anatomical situation and the goal of surgery. The most common technique is to perform direct cerebral revascularization through an extracranial to intracranial (EC-IC) bypass. This can be achieved either through a pedicled bypass graft,

✉ L. Wessels
Lars.Wessels@charite.de

[1] Department of Neurosurgery and Center for Stroke Research Berlin (CSB), Charité-Universitätsmedizin Berlin, Charitéplatz 1, 10117 Berlin, Germany

such as a superficial temporal artery to middle cerebral artery (STA-MCA) bypass, which is typically used for flow augmentation, or a free arterial or venous interposition graft, which is usually considered for complete flow replacement or flow augmentation in cases where a previous pedicled graft has failed or is unfeasible [6].

Apart from pedicled or non-pedicled grafts, an EC-IC bypass is additionally categorized according to the amount of blood that it provides: A "standard-flow" bypass is a pedicled graft that usually provides 20–70 ml/min. The most common example is an end-to-side anastomosis between the STA to an M4 segment of the MCA (STA-MCA bypass) [7] or to the distal posterior cerebral artery (PCA) [8], Modifications of this idea to use distal branches of the external carotid artery (ECA), such as the STA or maxillary artery (MA), as a pedicled donor vessel are occipital artery (OA) to PCA [9], MA to MCA [10], or anterior STA to anterior cerebral artery (ACA) [11]. The next level of flow is provided through "intermediate-flow" interposition grafts using the radial artery as an interposition graft with flow rates between 60 and 100 ml/min. Most commonly, this intermediate-flow radial artery interposition bypass jumps from the proximal ECA to an M2 segment branch of the MCA, but a large number of variations regarding the distal (intracranial) anastomosis site exist, such as ECA to PCA or ECA to ACA [12]. The highest level of flow is provided through a "high-flow bypass" using a saphenous vein interposition graft with flow rates between 100 and 200 ml/min [13, 14]. Next to the greater amount of flow compared to an intermediate- or standard-flow bypass, a saphenous vein graft also allows bypassing a greater distance, since a radial artery graft is usually limited to 23–25 cm in length or to obtain revascularization of multiple vascular territories. Next to the proximal ECA, a saphenous vein interposition bypass can therefore also originate from more distal extracranial vessels, such as the subclavian artery, in selected cases where the ECA or common carotid artery (CCA) is occluded. On the intracranial side, typical recipient vessels are the M2 branches of the MCA or the large proximal branches of the ACA and PCA. To lower the risk of perioperative ischemia due to temporary clipping of the intracranial recipient vessel(s) during the distal anastomosis, the Excimer laser-assisted non-occlusive anastomosis (ELANA) technique offers an alternative of performing an intracranial saphenous vein anastomosis at the level of the ICA/M1 segment bifurcation without the need of temporary recipient vessel occlusion [15]. Depending on the number of vascular territories that require revascularization through any interposition graft, different revascularization techniques apart from grafting an intracranial end-to-side anastomosis are possible, such as multiple reinsertion [16] or double-barrel Y-bypass [17] techniques, among others.

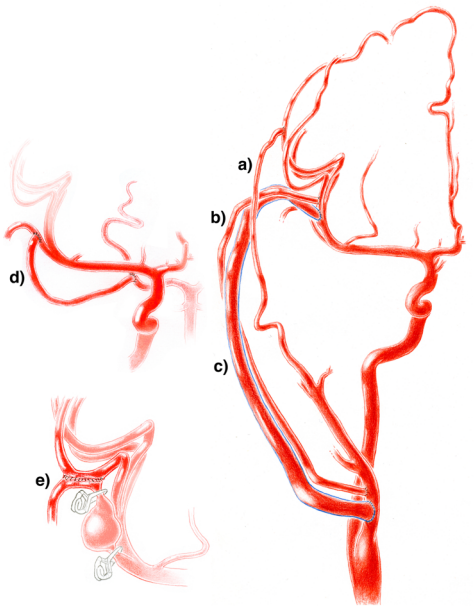
In addition to EC-IC bypass strategies, in situ bypass and IC-IC bypass provide alternative techniques for flow replacement via redistribution between intracranial vascular territories. The most common example of an in situ bypass is a side-to-side anastomosis between the posterior inferior cerebellar arteries (PICA-PICA bypass), which for example allows occlusion of one PICA distal to the anastomosis in order to treat an ipsilateral fusiform or distal PICA aneurysm [18]. For IC-IC bypass, an interposition graft (e.g., radial artery graft) is installed between two intracranial vessels (e.g., MCA-ACA) [12]. Importantly, diameters of the vessels intended for anastomosis should match and the surgeon should be aware of the increased risk of perioperative ischemia due to the fact that IC-IC grafting and in situ bypass regularly require consecutive temporary occlusion of two intracerebral vessels.

Indications

Cerebral bypass surgery for flow augmentation

Chronic cerebral ischemia caused by progressive stenosis of the cerebral arteries is responsible for approximately 10% of all ischemic strokes [19]. In patients with significantly reduced cerebrovascular reserve capacity (CVRC), the individual 2-year stroke risk ranges between 20 and 30%. The most common cause for hemodynamic stroke is arteriosclerotic cerebrovascular disease [20, 21], next to Moyamoya disease (MMD) with progressive idiopathic stenosis of the proximal cerebral vasculature.

In general, all patients with chronic cerebral ischemia and underlying steno-occlusive cerebrovascular disease require functional (quantitative) brain perfusion imaging (i.e., positron emission tomography (PET) or single-photon emission computed tomography (SPECT) imaging) with measurement of the CVRC, for example, following acetazolamide application [22], in order to stratify the individual stroke risk depending on the degree of hemodynamic impairment [20]. In cases with a reduced CVRC, flow augmentation through bypass grafting (typically STA-MCA) was previously shown to result in hemodynamic rescue [23] and also improve functional neurological outcome via motor plasticity [24]. Although STA-MCA bypass surgery was shown to reduce the 10-year stroke risk from 19.6 to 9.4% in patients with MMD [25] interestingly, the randomized controlled trial on bypass surgery for treatment of cerebral hemodynamic impairment (Carotid Occlusion Surgery Study (COSS)) failed to show a clear benefit of bypass surgery in patients with arteriosclerotic ICA occlusion, mainly due to a high perioperative stroke rate up to 15% [26]. Mainly, this negative result has been attributed, by some authors, to the limited experience in surgery and management of cerebrovascular bypass patients of many of the participating centers, next to the short follow-up of 2 years, up until when the incidence rate of stroke in medically managed patients started to cross the stroke incidence rate of 21% in bypass patients. On the other hand, high-volume centers



Bypass type	Common techniques	Typical indications
a) Standard flow (20-70 ml/min)	STA-MCA[7] STA-PCA[8] STA-ACA[11]	Chronic cerebral ischemia in Moyamoya vasculopathy and arteriosclerotic cerebrovascular disease with hemodynamic compromise Vessel sacrifice with needed blood flow of 20-70 ml/min, Tumors and aneurysms with chronic ischemia
b) Intermediate flow (60-100 ml/min)	ECA-MCA[3,14] ECA-ACA[13,14] ECA-PCA[13,14] Direct end-to-side, multiple reimplantation[16] or Y-bypass[17]	Chronic cerebral ischemia, failed STA-MCA or no STA Vessel sacrifice with needed blood flow of 60-100ml/min
c) High flow (100-200 ml/min)	ECA-MCA[12] ECA-PCA[12] ECA-ACA[12]	Vessel sacrifice with needed blood flow of 100-200 ml/min
d) IC-IC	M2-P2 Radial artery graft	Revascularisation of posterior circulation
e) In-situ	PICA-PICA[18] MCA reanastomosis [12]	Aneurysms, most often used in PICA aneurysms Complex M3 aneurysms

Fig. 1 In (a)–(c), all three types of EC-IC bypass are shown with the provided blood flow and the common indications as well as with the typical technical variations. In (d), an IC-IC bypass from the MCA to a P2 segment is shown. In (e), in situ bypass between the two M2 segments after aneurysm trapping is shown

have consistently shown that STA-MCA bypass grafting can be safely performed with a perioperative stroke risk as low as 3–7% [1, 3, 27–29]. Together with the results of a COCHRANE analysis [30], this suggests that bypass surgery for hemodynamic compromise is indeed safe and effective, provided that bypass surgery remains limited to highly specialized centers [31, 32].

Next to a high level of specialization, different tools, such as intraoperative neuro-monitoring, non-invasive recipient vessel identification, and assessment of bypass patency

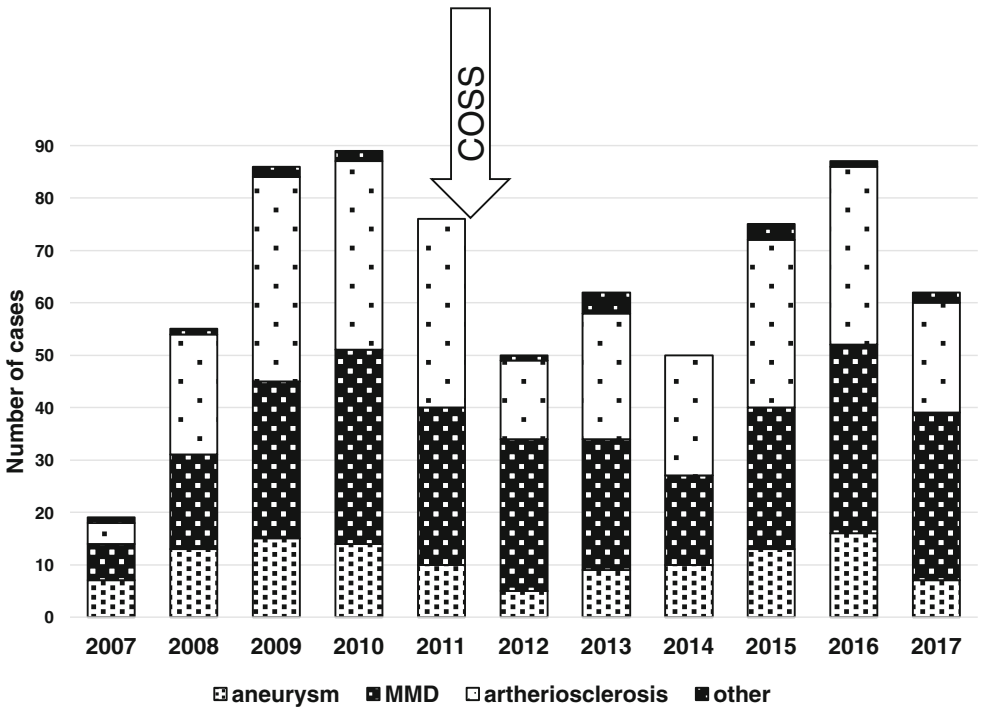


Fig. 2 The number of bypass cases in each year from 2007 until August 2017 treated in our center is shown, differentiated by indication. The arrow indicates the publication of COSS [25]

through indocyanine green-video angiography (ICG-VA with Flow800) and semi-quantitative cerebral perfusion assessment through Laser Speckle Imaging have helped to improve patient outcomes and intraoperative workflow [28, 33, 34]. Lastly, standardization—for example, by performing a targeted craniotomy above the end of the Sylvian fissure, where a suitable M4 recipient vessel is most frequently encountered—may help further increase the success rate of an STA-MCA bypass [35].

Cerebral bypass surgery for flow replacement

Bypass grafting for flow replacement has the goal to prevent acute ischemic stroke following proximal vessel occlusion and remains the treatment of choice for treatment of complex aneurysms (i.e., dolichoectatic, giant (> 2.5 cm), partially thrombosed or calcified, precoiled, or fusiform) that are not open to direct clipping/clip reconstruction or endovascular treatment [12, 16, 17] and resection of skull base tumors that require proximal vessel sacrifice [36]. To estimate the required amount of blood flow that needs to be provided through the graft, a preoperative balloon test occlusion (BTO) should be routinely performed for the anterior circulation. During this endovascular procedure, a balloon catheter is inflated inside the ICA. During the occlusion, quantitative CBF in the vascular territory of interest is monitored by a parenchymal thermal diffusion probe [37] and the CVRC is quantified following acetazolamide application. Depending on (a) whether or not transient neurological deficits occur, (b) the immediate perfusion response, and (c) the degree of hemodynamic CVRC impairment during the occlusion, the amount of bypass flow required to prevent ischemia can be estimated [13] (Fig. 1). Besides the decision on how to bypass the diseased vessel segment, the surgeon also has to decide on how to handle the aneurysm. The most effective strategy is to trap the aneurysm since this will result in immediate cure of the vascular pathology. If, however, perforating arteries originate from the aneurysm, trapping of the aneurysm is not possible without the risk for ischemia. In these cases, proximal occlusion, resulting in flow stasis or flow reversal in the aneurysm, is mostly sufficient, leading to intra-aneurysmatic thrombosis and aneurysm occlusion. If proximal occlusion is not possible, distal occlusion can be performed.

Other less frequent bypass indications with the goal to prevent acute cerebral ischemia include management of unintended intraoperative vessel damage, when direct vessel repair is impossible [36]. In contrast, reports of direct revascularization in acute stroke, for example, after failed endovascular recanalization or in progressive acute stroke [38] should be regarded critically due to the high risk of hemorrhagic transformation.

In our center, we performed 711 cerebral bypass procedures from 2007 until August 2017 in different indications mostly for flow augmentation in MMD patients and in patients suffering from arteriosclerotic cerebral vessel occlusion (Fig. 2). After publication of COSS [26], the number of patients with arteriosclerotic vessel occlusion dropped. But in the following years it raised again, with the difference that the indication changed from isolated ICA stenosis to multi-vessel disease. These patients are often suffering from arteriosclerotic stenosis of all vessels maintaining blood flow to the brain with progressive clinical symptoms based on this chronic cerebral ischemia. To prove the beneficial effect of cerebral revascularization in this indication, prospective studies should be performed.

In conclusion, although an STA-MCA bypass remains the most common bypass type, the continuously developed techniques for cerebral bypass grafting are diverse and permit an individually tailored approach to suit the individual indication. In general, a high level of standardization and restriction of cerebral bypass surgery to highly specialized vascular centers should be targeted to ensure patient safety and optimize clinical outcomes.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval No patient-related data.

Informed consent No patient-related data.

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