Bypass strategies for common carotid artery occlusion

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Abstract

Background Common carotid artery occlusion (CCA-occlusion) is a rare condition where standard revascularization is not feasible. Here, we analyzed our experience with surgical revascularization of CCA-occlusion to develop an algorithm for selection of the most suitable bypass strategy according to the Riles classification.

Methods During a 10-year period, 16 out of 288 patients with cerebrovascular disease and compromised hemodynamic reserve underwent revascularization for unilateral CCA-occlusion. The utilized bypass strategies included (1) a saphenous vein graft from the subclavian artery (SA) to the internal carotid artery (ICA), (2) a radial artery graft from the V3 segment of the vertebral artery (VA) to a superficial branch of the middle cerebral artery (MCA), or (3) a saphenous vein graft from the SA to a deep branch of the MCA.

Results In CCA-occlusion with maintained external carotid artery (ECA)/ICA patency (Riles type 1A), an SA-ICA bypass was performed (25%). In cases without ECA/ICA patency (Riles type 1B or 2) but suitable VA, a VA-MCA bypass was grafted (31%). In cases with unsuitable VA, a long SA-MCA interposition bypass was performed (38%). Transient postoperative neurological deficits occurred in 5 patients (31%) with 1 patient (6%) suffering permanent neurological worsening and 1 mortality (6%). Overall, no difference was found between the median preoperative mRS (2; range, 1–4) and the mRS at the time point of the last follow-up (2; range, 1–6; $p = 0.75$). The long-term graft patency was 94%.

Conclusions Although surgical revascularization for CCA-occlusion is feasible, it is associated with a higher risk than standard bypass grafting. Considering the poor natural history of CCA-occlusion, however, this risk may be justified in carefully selected patients.

Keywords Cerebral revascularization · Common carotid artery occlusion · Chronic cerebral ischemia · Extracranial–intracranial bypass · Hemodynamic stroke

Introduction

Common carotid artery occlusion (CCA-occlusion) is a rare condition and diagnosed in approximately 3% of all patients with symptomatic cerebrovascular disease [9]. Typically, affected patients present with transitory ischemic attacks (TIAs)

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or ischemic stroke due to chronic cerebral hemodynamic compromise. Although the natural history data for patients with CCA-occlusion remains limited, the fact that 93% of patients with CCA-occlusion are symptomatic with either transitory ischemic attacks (TIAs) or ischemic stroke [3, 14] suggests that CCA-occlusion is associated with an even higher risk of cerebral ischemia than occlusion of the ICA alone [7, 18]. At present, randomized controlled trials for the treatment of CCA-occlusion do not exist but the most recent guidelines of the American Heart Association recommend surgical treatment of symptomatic ischemic lesions affecting the anterior cerebral circulation [5]. In contrast to internal carotid artery occlusion (ICA-occlusion), however, ipsilateral flow via the external carotid artery (ECA) is not present in CCA-occlusion and standard revascularization strategies like grafting of a superficial temporal artery to middle cerebral artery (STA-MCA) bypass or an ECA-MCA interposition bypass are not feasible [22]. Thus, treatment of symptomatic CCA-occlusion

remains complicated and less straightforward than treatment of ICA-occlusion and there is no consensus on the ideal strategy for surgical revascularization.

According to Riles and colleagues, 3 main types of CCA-occlusion can be distinguished: type 1A (CCA-occlusion with patent bifurcation, ~ 62%), type 1B (CCA-occlusion plus ICA-occlusion, ~ 27%), and type 2 (CCA-occlusion plus ICA- and ECA-occlusion, ~ 11%) [14, 19]. CCA-occlusion plus ECA-occlusion (type 1C) should be regarded as a theoretical variant, since its occurrence ranges between 0 and 2.5% [3, 14]. In this report, we analyzed our experience with surgical revascularization of symptomatic CCA-occlusion and present 3 bypass strategies that are described in detail based on an algorithm for selecting the ideal bypass option depending on the type of CCA-occlusion.

Methods and materials

Study design

The study was approved by the local ethics committee of the Charité University Hospital in Berlin, Germany (EA2/178/18), and performed in compliance with Health Insurance Probability and Accountability Act regulations. Between January 1st, 2007, and December 31st, 2017, patients that suffered hemodynamic compromise due to unilateral CCA-occlusion and received surgical revascularization for flow augmentation were retrospectively identified and included in the present study. Demographic, clinical, and radiographic patient data, the selected bypass strategy, procedure-related complications, bypass patency, and clinical outcome according to the modified Rankin Scale (mRS) at the time point of discharge and at 6- or 12-month follow-up were collected by a clinician who was not directly involved in the patients' care (L.W.).

Patient management

All patients were anesthetized with propofol and remifentanil. Heart rate, arterial blood pressure, peripheral oxygen saturation, body temperature, and motor and somatosensory evoked potentials (MEP and SEP) were monitored continuously. The intraoperative mean arterial pressure (MAP) was targeted at 90–100 mmHg. Arterial blood gases were sampled every 30 min and the end-expiratory carbon dioxide concentration was maintained at a level corresponding to an arterial partial pressure of CO_2 between 38 and 42 mmHg. Postoperatively, patients were transferred to our neurosurgical intensive care unit for blood pressure maintenance targeting a systolic pressure between 120 and 140 mmHg for the first 12–24 h. To rule out procedure-related hemorrhage or infarction and confirm postoperative bypass patency, computerized tomography (CT)

with CT-angiography (CT-A) was performed no later than on postoperative day 1. Additional CT/CT-A or magnetic resonance imaging (MRI) was performed depending on the occurrence of secondary neurological worsening. To assess bypass function, digital subtraction angiography (DSA) was performed intraoperatively (robotic Artis Zeego® II, Siemens Healthcare, Forchheim, Germany) or on postoperative days 5 to 7 in addition to follow-up DSA at 3 and 12 months according to our standard protocol for interposition bypass grafting.

Determination of bypass strategy

To determine the bypass strategy, all patients received a preoperative MRI and DSA to rule out large areas of infarction and characterize the pattern of collateralization. To then determine the presence or absence of type 1A CCA-occlusion, all patients underwent duplex sonography to evaluate the patency of the ipsilateral ICA by confirmation of retrograde blood flow through the ECA, which cannot be identified with conventional MRI and DSA imaging. Accordingly, patients were categorized into one of the following 3 groups (Fig. 1):

1. CCA-occlusion with maintained ECA/ICA patency: Extracranial to extracranial (EC-EC) bypass from the subclavian artery (SA) to the ICA distal to the site of CCA-occlusion.
2. CCA-occlusion without ECA/ICA patency and large-bore vertebral arteries: Extracranial to intracranial (EC-IC) bypass from the V3 segment of the vertebral artery (VA) to an M2/M3 branch of the MCA.
3. CCA-occlusion without ECA/ICA patency and non-suitable/hypoplastic vertebral arteries: Long interposition graft from the SA to an M2/M3 branch of the MCA.

In general, saphenous veins were harvested for SA-ICA and SA-MCA bypass grafting because of the large diameter of the anastomosis and required the length of the graft (~ 40 cm for an SA-MCA bypass). For VA-MCA bypass grafting, a radial artery graft was chosen to accommodate the M3 recipient.

Surgical procedure

For SA-ICA bypass grafting, patients were positioned supine without rigid head fixation but with 30° rotation and 20° reclination of the head to facilitate access to the ipsilateral CCA bifurcation along the course of the sternocleidomastoid muscle. First, ultrasound was used to identify and expose the SA at its supraclavicular apex distal to the origin of the VA and the SA was prepared for the proximal anastomosis. Next, a second skin incision was performed along the course of the CCA bifurcation to

SA – ICA Bypass　　　　**VA – MCA Bypass**　　　　**SA – MCA Bypass**

Fig. 1 The 3 surgical revascularization strategies for the treatment of common carotid artery occlusion with hemodynamic compromise. Categorization is performed according to (**a**) maintained ECA/ICA patency (type 1A CCA-occlusion) and in cases without ECA/ICA patency (type 1B or type 2 CCA-occlusion) (**b**) suitability, or (**c**) non-suitability of the vertebral artery
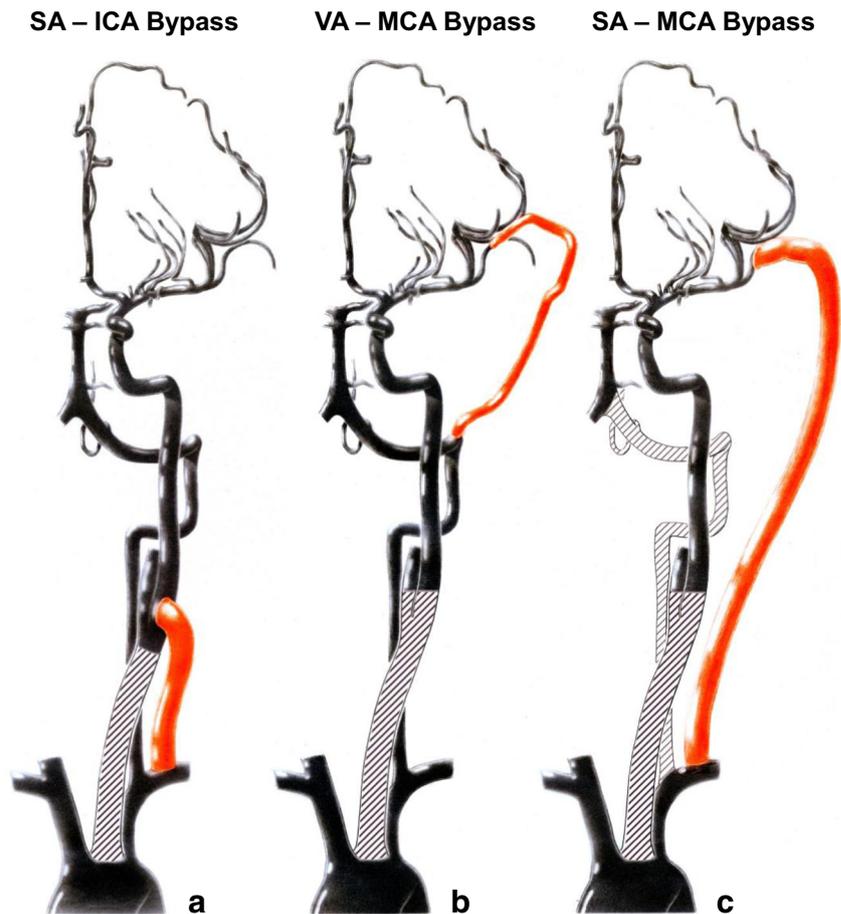
prepare the distal anastomosis site. Importantly, the anatomy and level of the carotid bifurcation must be considered because a high-situated CCA bifurcation requires a far distal dissection to mobilize the hypoglossal nerve and adequately expose the ICA. Then, the harvested saphenous vein was prepared, tunneled, and fish-mouthed and the proximal SA anastomosis was performed. Pigtail vascular clamps were used for temporary occlusion because of the insufficient closing force of aneurysm clips across the SA. The proximal anastomosis was sutured end-to-side in continuous or interrupted fashion with Prolene 7-0. It is important to consider that pronounced arteriosclerotic plaques are frequently encountered within the SA and therefore, a meticulous suturing technique is required to avoid intimal dissections. After completion of the anastomosis, a temporary clip was placed across the graft to avoid filling after removal of the pigtail vascular clamps. Next, patency of the ICA was confirmed by test-incision and checking for ICA backflow before performing the distal ICA anastomosis. After temporary clipping and cutting of the ICA, the distal part of the saphenous vein graft was sutured to the ICA stump in an end-to-end fashion with interrupted sutures. The completion of the distal anastomosis was followed by flow initiation through the graft.

The VA-MCA bypass was performed in line with our previous report describing an extracranial "posterior communicating artery bypass" for revascularization of patients with CCA-occlusion and suitable vertebral arteries [20]. After harvesting the radial artery, patients were positioned in park-bench and the lamina of C1 was exposed through a "lazy-S" incision. The use of a "lazy-S" incision instead of a straight midline incision is helpful to facilitate tunneling of the graft. Importantly, the "lazy-S" incision should be planned in a fashion that allows strict midline dissection at the level of C1 in order to avoid VA injury during the exposure. After C1 exposure, a hemilaminectomy with mobilization of the V3 segment of the VA was performed. For the preparation of the distal anastomosis, a craniotomy with exposure of the posterior end of the sylvian fissure was performed [16]. In case a suitable cortical recipient was not available, the fissure was opened. In order to facilitate the VA and MCA approaches without repositioning, the patient was secured with lateral support, which permitted 45° tilting of the operating table to both sides. After selection of a suitable recipient (preferably M3), the radial artery graft was tunneled and the proximal (VA) and distal (MCA) anastomoses were completed in end-to-side fashion with Prolene 7-0 and Declene 8-0, respectively.

For SA-MCA bypass grafting, patients were positioned supine with 45° head rotation and 10–20° reclination. A

saphenous vein graft with a length of ~40 cm was harvested and prepared. The ipsilateral donor (SA) was exposed as described above. In contrast to the recipient for the VA-MCA bypass, the preferable recipient for the SA-MCA bypass was an M2 segment due to the greater diameter of the saphenous vein graft and consequently, a pterional exposure was performed. After identification of a suitable recipient, the proximal and distal end-to-side anastomoses were completed with Prolene 7-0 and Declene 8-0, respectively.

In all cases, a 5-min test occlusion with continuous MEP/SEP monitoring was performed for recipient vessel selection. For additional ischemic protection during the anastomosis, the fraction of inspired oxygen was adjusted to 1.0 (100%). Upon completion of the distal anastomosis, a loading dose of 300-mg acetylsalicylic acid was administered intravenously before flow initiation through the graft and intraoperative bypass patency was assessed by indocyanine green (ICG) videoangiography [23].

Statistical analysis

Descriptive summary statistics are presented as mean ± standard deviation, median and range (minimum–maximum), or percentage, as appropriate. Statistics were calculated with GraphPad Prism for Mac (Version 8.1.0, GraphPad Software, San Diego, CA, USA). A two-tailed Wilcoxon matched pairs signed rank test was used to compare outcome according to the mRS score. Statistical significance was set at $p < 0.05$.

Results

Patient characteristics

During the 10-year period, 288 patients with arteriosclerotic cerebrovascular disease and hemodynamic compromise were treated with 318 bypass procedures at our institution and 16/288 (6%) patients underwent surgical revascularization for unilateral CCA-occlusion. The mean patient age was 63 ± 9 years with predominant affection of the left hemisphere (63%) and male gender (94%). Patients presented with symptoms from previous hemodynamic transitory ischemic attacks (TIAs) or stroke with a median mRS of 2 (range, 1–4). Medical interventions prior to bypass grafting included blood pressure management, platelet inhibition, and statin therapy. Preoperative functional cerebral blood flow (CBF) measurements revealed a compromised cerebrovascular reserve (Table 1).

Surgery

SA-ICA bypass was used in 4 patients (25%) (Fig. 2), VA-MCA bypass in 5 patients (31%) (Fig. 3), and SA-MCA bypass in 6 patients (38%) (Fig. 4). In 1 patient (6%) with CCA-occlusion and a patent ECA (Riles type 1B), a saphenous vein interposition bypass from the SA to the external carotid artery (ECA) with subsequent superficial temporal artery to middle cerebral artery (STA-MCA) bypass was performed. The median temporary clipping time of the recipient vessel was 18 min (range, 15–21).

Outcome

Bypass patency according to ICG videoangiography was confirmed in all patients. Early asymptomatic graft occlusion was noted in 1/16 patients (6%) on DSA performed within 1 week after the procedure. Transient postoperative neurological deficits that were completely resolved at the time point of the latest follow-up occurred in 4/16 patients (25%) with unremarkable postoperative imaging. Radiographic ischemic or hemorrhagic complications were observed in 4/16 patients (25%) with 2/16 patients (12.5%) suffering permanent neurological worsening: Patient no. 5 (VA-MCA bypass) suffered a peri-sylvian frontal hemorrhage and seizure on postoperative day 1 that required reintubation, sedation, and blood pressure management. Patient no. 8 suffered a massive intracerebral hemorrhage 6 h after the procedure that ultimately led to withdrawal of care. Accordingly, the overall procedure-related morbidity and mortality was 6% and 6%, respectively. The median hospitalization time was 14 days (range, 3–42 days) and no statistical difference was found between the median preoperative mRS (2; range, 1–4) and the mRS at the time point of the last follow-up at 6 or 12 months (2; range, 1–6; $p = 0.75$) (Fig. 5).

Discussion

In this study, we present an approach for cerebral revascularization of symptomatic CCA-occlusion through 3 different bypass strategies depending on the 3 most common patterns of CCA-occlusion with consideration of the vertebral artery development (Fig. 6). Our results suggest that surgical revascularization for CCA-occlusion is feasible but associated with a higher periprocedural risk than standard STA-MCA bypass grafting.

Considering the increased complexity of bypass procedures for revascularization of multivessel disease like CCA-occlusion, patients need to be correctly stratified in order to individually tailor the surgical strategy and minimize the perioperative risk. This need for standardization is mirrored by the results of a large review on CCA-occlusion that identified 21 studies that describe more than 15 microsurgical and endovascular techniques for extra- and intracranial revascularization of all types of CCA-occlusion [14]. In our series, only 16 out of 288 patients (6%) suffered unilateral CCA-

Table 1 Demographic and clinical data

No.	Age, sex	Diagnosis	CVRC	Riles type	Suitable VA	Bypass strategy	Graft type	Graft patency	Graft flow (ml/min)	Transient post-OP deficit	Permanent post-OP deficit	New ischemic/hemorrhagic lesion	Pre-OP mRS	Post-OP mRS	Follow-up mRS
01	52, m	L CCAO	↓ (SPECT)	1B	+	SA-ECA + STA-MCA	SVG	+	60	−	−	−	1	1	1
02	49, m	L CCAO	→ (H$_2$O PET)	1B	+	SA-M2	SVG	+	160	−	−	+/−	1	1	1
03	81, m	R CCAO	↓ (SPECT)	2	+	VA-M3	RAG	+	65	−	−	−	1	1	1
04	69, m	L CCAO	N/A	2	−	SA-M3	SVG	+	100	+	−	−	2	4	2
05	71, f	L CCAO	→ (H$_2$O PET)	2	+	VA-M2	SVG	+	50	+	+	−/+	3	4	4
06	72, m	R CCAO	→ (H$_2$O PET)	2	−	SA-M2	SVG	+	120	−	−	−	3	3	3
07	61, m	L CCAO	N/A	1A	N/A	SA-ICA	SVG	+	165	−	−	−	4	4	4
08	67, m	L CCAO	↓ (SPECT)	2	−	SA-M2	SVG	+	90	−	+	−/+	3	6	6
09	72, m	L CCAO	→ (H$_2$O PET)	2	+	VA-M3	RAG	+	55	−	−	−	1	1	1
10	48, m	L CCAO	↓ (SPECT)	1B	−	SA-M2	SVG	+	120	+	−	−/+	2	2	2
11	66, m	L CCAO	↓ (SPECT)	1A	N/A	SA-ICA	SVG	+	70	+	−	−	2	2	2
12	55, m	R CCAO	↓ (SPECT)	2	+	VA-M2	RAG	+	60	−	−	−	2	2	2
13	68, m	R CCAO	↓ (SPECT)	2	+	VA-M2	RAG	−	20	−	−	−	2	2	2
14	61, m	R CCAO	↓ (SPECT)	1A	N/A	SA-ICA	SVG	+	100	+	−	−	1	2	1
15	56, m	R CCAO	↓ (SPECT)	2	−	SA-M2	SVG	+	150	−	−	−	3	3	3
16	64, m	L CCAO	↓ (Xe CT)	1A	N/A	SA-ICA	SVG	+	N/A	−	−	−	1	1	1

No., number; *m*, male; *f*, female; *L*, left; *R*, right; *CCAO*, common carotid artery occlusion; *CVRC*, cerebrovascular reserve capacity; *SPECT*, single photon emission computed tomography; *PET*, positron emission tomography; *Xe CT*, xenon-enhanced computed tomography; *N/A*, not applicable; *ECA*, external carotid artery; *ICA*, internal carotid artery; *VA*, vertebral artery; *SA*, subclavian artery; *STA-MCA*, superficial temporal artery–middle cerebral artery; *M2 or M3*, M2 or M3 segment of the middle cerebral artery; *SVG*, saphenous vein graft; *RAG*, radial artery graft; *mRS*, modified Rankin Scale
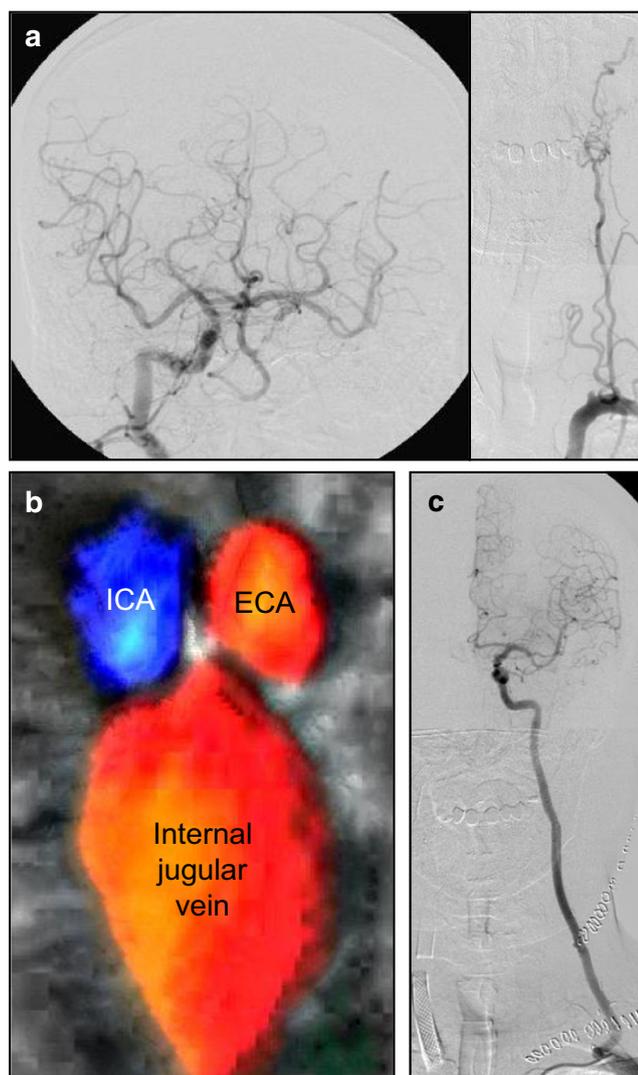
Fig. 2 **a** The preoperative angiogram of patient 7 confirmed a left-sided CCA-occlusion. **b** Preoperative duplex sonography of the left CCA bifurcation yielded retrograde external carotid artery (ECA) flow with antegrade filling of the internal carotid artery (ICA) across the CCA bifurcation, which allowed an extracranial–intracranial revascularization strategy in form of a subclavian artery (SA)–internal carotid artery (ICA) bypass distal to the site of CCA-occlusion. **c** The postoperative angiogram confirms a patent SA–ICA saphenous vein interposition graft with filling of the left ICA territory

occlusion, which is in line with the reported low incidence of the disease. Similar to previous studies, we also noted a male predominance and mean patient age around 63 years [3, 14]. However, only 37% of our patients presented with TIAs, whereas 63% presented with ischemic stroke, which differs from the previously reported TIA and ischemic stroke rates of 58% and 24%, respectively [3, 14]. Possibly, the more frequent detection of ischemic stroke upon presentation in our cohort is associated with the higher sensitivity of MR imaging, which was used for all patients in our cohort and previously not addressed [14].

Taking the 3 main types of CCA-occlusion into account, in our experience, the most straightforward surgical approach can be performed in CCA-occlusion with patency of the ECA/ICA bifurcation (Riles type 1A) [4, 19], which we encountered in 25% of our patients. In general, we found that such type 1A CCA-occlusion can be revascularized by a saphenous vein graft connecting the ipsilateral SA to the proximal ICA beyond the point of CCA-occlusion. Naturally, this strategy requires patency of the ECA/ICA bifurcation, which can be easily missed because digital subtraction angiography will not visualize retrograde ECA flow into the ICA in the setting of proximal CCA-occlusion. Following our initial diagnostics with a conventional angiogram and MRI, we therefore routinely performed Doppler sonography of the affected CCA bifurcation to specifically determine the maintenance of ECA/ICA patency. Most importantly, the sensitivity and specificity of Doppler sonography for the determination of maintained ECA/ICA patency in our series was 100%, which limits the need for routine ICA test incision in cases of a preoperatively unknown occlusion type and minimizes the risk of having to re-adjust the individually planned revascularization strategy during surgery. Further, we considered a venous SA-ICA interposition bypass as the strategy of choice, because it provides a high-flow conduit and has a favorable risk profile compared with bypass strategies with an intracranial anastomosis that require a craniotomy, longer graft, and are associated with technical difficulties when performing microsurgical anastomoses in deep corridors with vessels of different calibers.

Apart from type 1A occlusion, the incidence of patients *without* ECA/ICA patency (types 1B and 2) was 75% in our series and higher than in previous reports [3, 14, 19]. This is noteworthy, because revascularization strategies for CCA-occlusion are most limited in the setting of complete CCA- and ICA-occlusion (with or without ECA-occlusion) and in particular type 2 CCA-occlusion was originally even classified as inoperable [19]. However, Riles and colleagues did not consider a revascularization strategy where the V3 segment of the vertebral artery could serve as a donor for a radial artery interposition graft to an ipsilateral MCA branch, thereby serving as a "posterior communicating artery" bypass between the anterior and posterior circulation [20]. In general, we defined "suitability" of the VA by the presence and patency of 2 large-bore vertebral artery segments from V1 to V4. The benefits of the VA-MCA bypass are the lower size mismatch between the interposition graft and the donor/recipient vessels, the shorter graft length, and the favorable course of the graft alongside the skull compared with a saphenous vein interposition graft from the SA to the MCA reported below. Consequently, the VA-MCA bypass has become our option of choice for revascularization of type 2 or type 1B occlusion, because alternative strategies, such as the "bonnet" bypass [6] or "reverse" STA-MCA bypass [2], appear more challenging regarding surgical

Fig. 3 Patient 5 suffered a left-sided CCA-occlusion without ECA / ICA patency. Due to bilaterally patent and suitably developed vertebral arteries, an extracranial–intracranial revascularization strategy in form of a vertebral artery (VA)–middle cerebral artery (MCA) bypass was chosen: **a** The intraoperative lateral angiogram shows filling of the left MCA territory through a saphenous vein interposition graft from the left V3 segment to a left M2 branch. **b** 3-dimensional postoperative CT-angiographic reconstruction of the VA–MCA bypass and postoperative CT imaging (**c**)
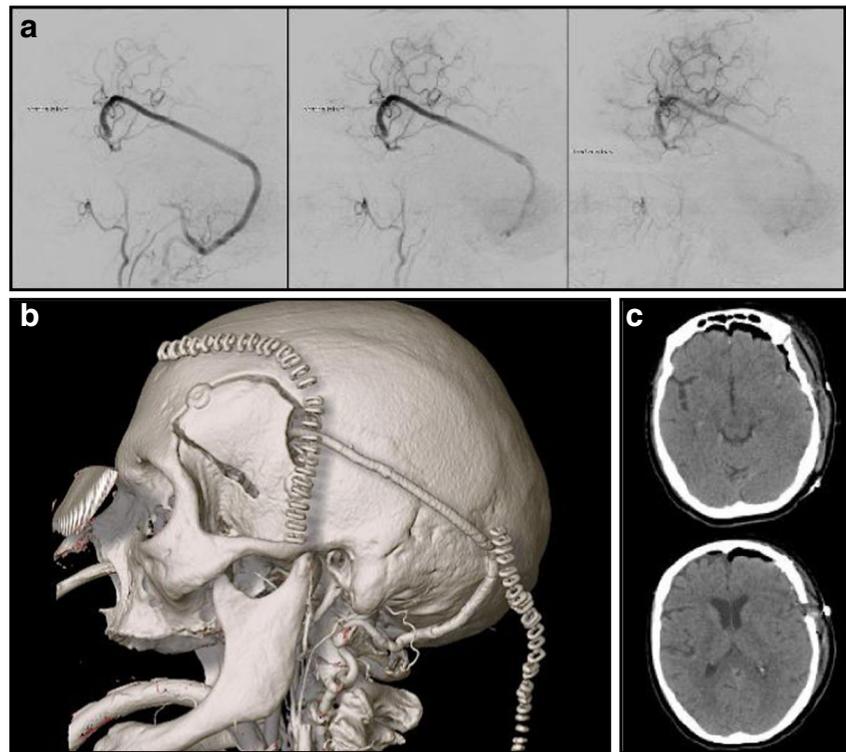
workflow, exposure, and intraoperative positioning [6] or remain hampered by a limited hemodynamic effectiveness [2]. Most importantly, the VA-MCA bypass can be applied not only in type 1B and type 2 CCA-occlusion but also in patients with bilateral occlusive disease and does not require repositioning.

The main reason why the VA-MCA bypass may not be suitable for type 1B or type 2 CCA-occlusion is non-suitability of the VA due to hypoplasticity, stenosis, or occlusion of one or both VAs. Here, a possibility for revascularization is to perform an EC-IC bypass from the SA to an MCA branch with a saphenous vein graft, because the radial artery is too short to bridge the required distance. Apart from the distance, an additional challenge is the need for a large caliber recipient, preferably an M2 branch. Further, the proximal SA anastomosis can be technically challenging because most neurosurgeons are not familiar with this anatomic region. Another alternative for revascularization specifically of type 1B occlusion is to perform a saphenous vein interposition graft from the SA to the ECA with subsequent grafting of an STA-MCA bypass. Although this was in fact performed in our first type 1B patient, we would no longer advocate this strategy because the main conduit for flow replacement in this case is not a large caliber interposition graft but the most likely arteriosclerotic distal ECA. Further, grafting of 3 instead of 2 anastomoses is required.

Our outcome analysis needs to be interpreted with caution due to the low patient number but it remains noteworthy that although 31% of our patients experienced temporary neurological deficits, the combined morbidity and mortality in our series was only 12.5%. A reason for the discrepancy could be the occurrence of postoperative hyperperfusion syndrome [12, 17], because 4 out of 5 patients with temporary deficits had unremarkable postoperative imaging studies and both patients with permanent neurological injury suffered intracerebral hemorrhage, which represents a rare but known complication following carotid revascularization [15]. Further, symptomatic hyperperfusion without hemorrhage often mimics the clinical presentation of ischemic stroke with sudden onset, upper extremity motor dysfunction, aphasia, dysarthria, and seizure activity, which we also observed in our affected cohort. Although all patients with temporary postoperative neurological deficits had intraoperative bypass flow rates at or above 100 ml/min, interestingly, no difference was found between these 4 patients (mean flow, 110 ± 12 ml/min) and 11 patients without transient neurological deficits (mean flow, 85 ± 49 ml/min; $p = 0.418$ two-tailed t test). Most likely, this observation is influenced by the limited patient number but on the other hand, the occurrence of asymptomatic patients with flow rates above 100 ml/min also suggests that postoperative hyperperfusion syndrome depends on a more complex interaction of factors that influence flow redistribution apart from the net flow increase alone, such as baseline flow characteristics, postoperative flow reversal, or the
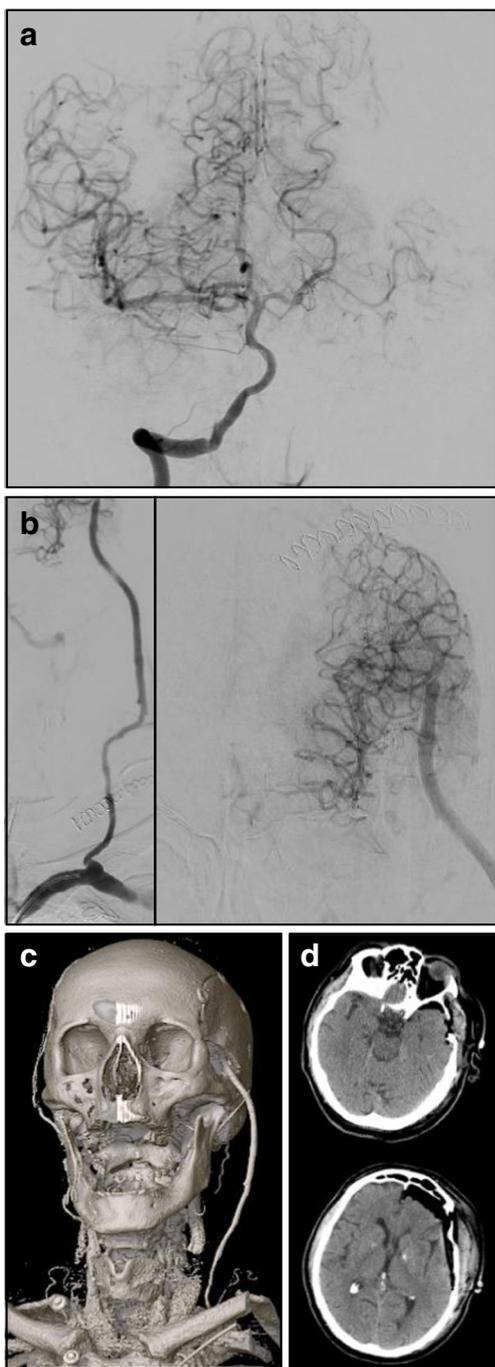
Fig. 4 Patient 4 suffered a left-sided CCA- and vertebral artery occlusion without ECA/ICA patency (**a**). Consequently, an intracranial–extracranial revascularization strategy in form of a subclavian artery (SA)–middle cerebral artery (MCA) bypass was chosen: **b** The postoperative anterior-posterior angiograms show the course of the patent saphenous vein interposition graft (left panel) from the SA to an M3 segment with filling of the ipsilateral MCA territory (right panel). **c** 3-dimensional postoperative CT-angiographic reconstruction of the SA–MCA bypass and postoperative CT imaging (**d**)

vascular target territory and order of the recipient vessel (i.e., M2 or M3). Nevertheless, intraoperative perfusion monitoring in addition to neuromonitoring may be
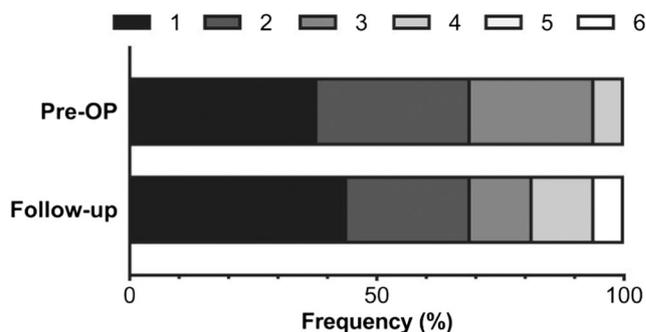

Fig. 5 Bar graphs illustrating the frequency distribution of clinical outcome according to the preoperative modified Rankin Scale (mRS) score compared with the time point of the latest follow-up at 6 or 12 months. $p = 0.75$; two-tailed Wilcoxon matched pairs signed-rank test

helpful to assess the risk for hyperperfusion already intraoperatively with distinction from ischemic stroke [10, 11]. Another limitation of our study is that we cannot provide information on postoperative functional CBF studies, because none of the surviving 15 patients remained symptomatic for hemodynamic events and consequently, there was no clinical need to perform follow-up functional CBF studies.

Overall, an argument cannot be made that revascularization of CCA-occlusion improved outcomes but rather that 87.5% of all patients remained neurologically stable in regard of their mRS score at the time point of the latest follow-up. Also, the 12.5% combined morbidity and mortality following revascularization of CCA-occlusion remains considerably higher than the periprocedural risk of STA-MCA bypass surgery [1, 8, 13, 21, 24]. However, the natural history of CCA-occlusion remains exceptionally poor with more than 90% of all patients being symptomatic and a likely suffering a higher hemodynamic stroke risk than in ICA-occlusion, since spontaneous EC-IC collateralization, for example via ophthalmic or meningeal collaterals, is not present in multivessel CCA-occlusion. Therefore, we believe that the benefit of treatment may justify the periprocedural risk in carefully selected patients
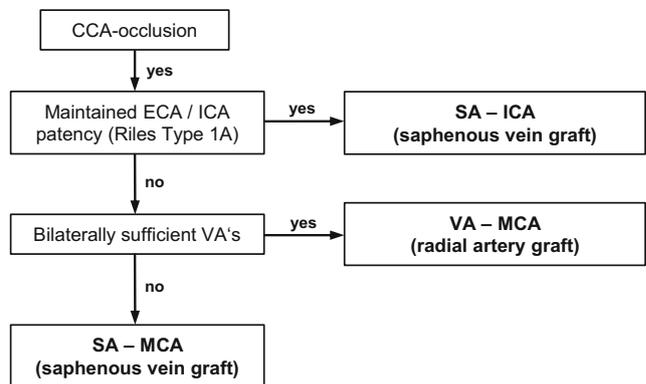

Fig. 6 Decision-making algorithm for surgical revascularization of CCA-occlusion with hemodynamic compromise. ICA, internal carotid artery; ECA, external carotid artery; MCA, middle cerebral artery; SA, subclavian artery; VA, vertebral artery

when considering the lack of therapeutic alternatives [3, 5, 14].

In conclusion, alternative bypass strategies offer a highly specialized approach for treatment of cerebral hemodynamic impairment due to multivessel CCA-occlusion. Most importantly, however, these strategies remain limited in their application and require additional surgical time and expertise, which must be weighed against the potential benefits of the procedure.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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 (ethics committee of the Charité University Hospital in Berlin, Germany; EA2/178/18) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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