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Tetsuya Tsukahara · Giuseppe Esposito
Hans-Jakob Steiger · Gabriel J.E. Rinkel
Luca Regli *Editors*

Trends in Neurovascular Interventions

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Edited by
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Tetsuya Tsukahara
Department of Neurosurgery, National Hospital Organization, Kyoto Medical Center, Kyoto, Japan

Giuseppe Esposito
Klinik für Neurochirurgie, UniversitätsSpital Zürich, Zürich, Switzerland

Hans-Jakob Steiger
Neurochirurgische Klinik, Universitätsklinikum Düsseldorf, Düsseldorf, Germany

Gabriel J.E. Rinkel
Department of Neurology, University Medical Centre Utrecht, Utrecht, The Netherlands

Luca Regli
Klinik für Neurochirurgie, UniversitätsSpital Zürich, Zürich, Switzerland

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Preface

The European-Japanese Joint Conferences for Stroke Surgery were initiated in Zürich in 2001 by Prof. Y. Sakurai and Prof. Yonekawa, under the name of "The Swiss-Japanese Joint Conference." The second meeting was also organized in Zürich two years later. The third meeting, under the name of "The European-Japanese Joint Conferences for Stroke Surgery," was held in 2006 in conjunction with the 70th Anniversary of the Neurochirurgische Universitätsklinik Zürich. The fourth meeting was organized in Helsinki, Finland, in 2008, with Prof. Hernesniemi as the congress president. The fifth European-Japanese Joint Conferences for Stroke Surgery was organized in Düsseldorf, Germany, in 2010.

The sixth meeting, under the name of "The European-Japanese Stroke Surgery Conference" (EJSSC), was organized from 2nd to 5th June 2012 in Utrecht, The Netherlands. The organizing and meeting chairmen were Prof. Luca Regli, Prof. Gabriel Rinkel and Prof. Tetsuya Tsukahara. The main topics of the conference consisted of surgical and endovascular management of intracranial aneurysm and arteriovenous malformations; current concepts in cerebral revascularization; and new developments in cerebrovascular imaging. A session on miscellaneous sessions and sessions on free topics completed the program.

The conference definitely provided an opportunity to gather the latest information on cerebrovascular disorders. A number of emerging concepts were presented and discussed. The conference facilitated networking to enhance the exchange of clinical and scientific knowledge between those in different cultures.

This volume presents the resulting original papers of the meeting.

Kyoto, Japan	Tetsuya Tsukahara
Zurich, Switzerland	Giuseppe Esposito
Düsseldorf, Germany	Hans-Jakob Steiger
Utrecht, The Netherlands	Gabriel J.E. Rinkel
Zürich, Switzerland	Luca Regli

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Intracranial Aneurysms

Surgical Decision-Making for Managing Complex Intracranial Aneurysms

Giuseppe Esposito and Luca Regli

Abstract The treatment of complex intracranial aneurysms remains a therapeutic challenge. These lesions are frequently not amenable to selective clipping or coiling or other endovascular procedures and surgery still has a predominant role.

We illustrate our "surgical decision making" for managing complex intracranial aneurysmal lesions. The best strategy is decided on the basis of pre-operative neuroradiological and intra-operative main determinants such as anatomical location, peri-aneurysmal angioanatomy (branch vessels, critical perforators), broad neck, intraluminal thrombosis, aneurysmal wall atherosclerotic plaques and calcifications, absence of collateral circulation, and previous treatment. The surgical strategy encompasses one of the following treatment possibilities: (1) Direct clip reconstruction; (2) Complete trapping ("classic" or "variant"); (3) Partial trapping (proximal "inflow" or distal "outflow" occlusion). Because the goal of any aneurysm treatment is both (1) aneurysm exclusion and (2) blood flow replacement, cerebral revascularization represents a major management option whenever definitive or temporary vessel occlusion is needed.

Cerebral revascularization can therefore be used temporarily as a "protective" bypass, or definitively as a "flow replacement" bypass.

Complete and partial trapping strategies are associated with flow "replacement" bypass surgery, to preserve blood flow into the territory supplied by the permanently trapped vessel. The construction of the "ideal" bypass depends on several factors, the most important of which are amount of flow needed, recipient vessel, donor vessel, and microanastomosis technique.

The choice between "complete" or "partial" trapping depends on angioanatomical criteria as well. A complete trapping is always favored, as it has the advantage of immediate aneurysm exclusion. When perforating vessels arise from the aneurysmal segment or when the inspection of all the angioanatomy of the aneurysm is considered inadvisable and risky, "partial trapping" strategies are of interest. Partial trapping may consist either of proximal or distal occlusion. We discuss the rationale behind these treatment modalities and illustrate it with a case series of seven patients successfully treated for complex intracranial aneurysmal lesions (location: 1 ICA, 1 ACom, 3 MCA, 2 PICA).

Keywords Complex intracranial aneurysms • Extra-to-intracranial bypass, giant aneurysms • Reconstruction • Partial trapping • Trapping • Trapping variant

Abbreviations

ACom	Aanterior communicating artery
CT	Computed Tomography
CT-A	Computed Tomography angiography
DSA	Digital Subtraction Angiography
EC-IC	Extra-to-intracranial
ELANA	Excimer Laser Assisted Non occlusive Anastomosis
IA	Intracranial aneurysm
ICA	Internal carotid artery
IC-IC	Intra-to-intracranial
ICG-VA	Indocyanine Green Video Angiography
MCA	Middle cerebral artery
MRA	Magnetic Resonance Angiography
MRI	Magnetic Resonance Imaging
mRS	Modified Rankin Scale
PICA	Posterior inferior cerebellar artery
STA	Superficial temporal artery
STA-MCA	Superficial temporal artery to middle cerebral artery

G. Esposito, MD (✉) • L. Regli, MD, PhD
Department of Neurosurgery, University Hospital Zurich, Frauenklinikstrasse 10, Zurich CH-8091, Switzerland
e-mail: giuseppe.esposito@usz.ch

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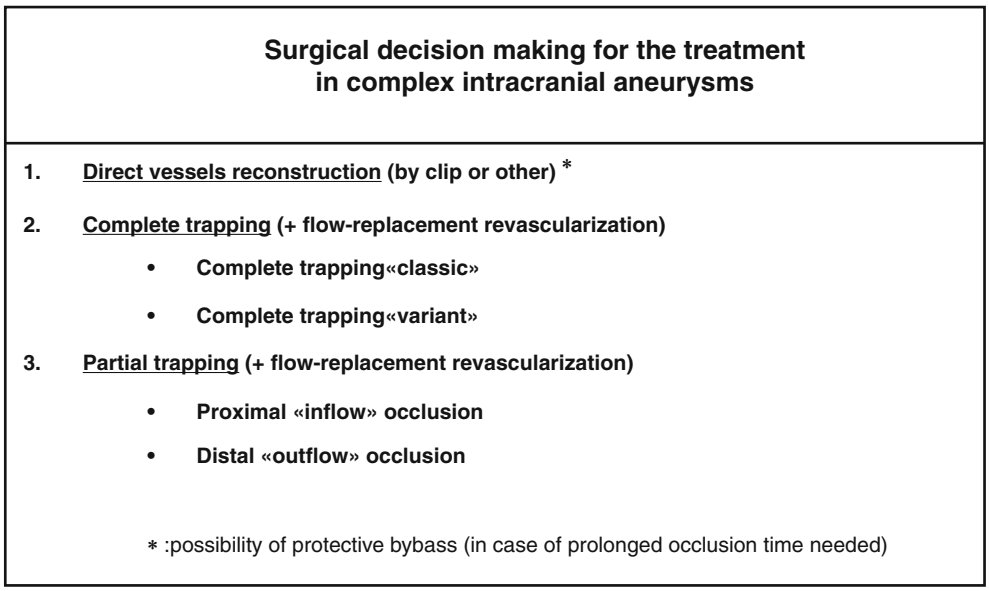

Fig. 1 Flow chart illustrating our strategies for managing complex intracranial aneurysms

Introduction

Complex cerebral aneurysms include both giant and large/small aneurysms, the complexity of which is due to anatomical location, peri-aneurysmal angioanatomy (branch vessels, critical perforators), broad neck, intraluminal thrombosis, atherosclerotic plaques or calcifications of the aneurysmal wall, absence of collateral circulation, and previous treatment [1, 4, 7, 8]. These lesions are frequently not amenable to selective clipping or coiling or other endovascular procedures. Their treatment remains a therapeutic challenge and surgery still has a predominant role [7]. Herein we present our surgical decision making for the treatment of intracranial complex aneurysmal lesions.

Materials and Methods

Pre-op Neuroimaging

A comprehensive understanding of the pre-op neuroimaging is mandatory. Pre-operative neuroradiological exams must include a CT angiography (CTA) and/or a digital subtraction angiography (DSA). 3D reconstruction sequences are very important for a detailed angioanatomical evaluation. When bypass surgery represents a possible treatment modality, either a DSA with injection of the external carotid artery or 3D-CTA of scalp vessels (namely, the superficial temporal artery – STA – and its branch, as well as the occipital artery) is performed.

Intra-operative Tools

To assess vessels' patency and direction of the flow, we use intraoperative Indocyanine green video angiography (ICG-VA) using a commercially available surgical microscope (OPMI® Pentero™, The Carl Zeiss Co., Oberkochen, Germany). Real-time ICG-VA images with arterial, capillary, and venous phases can be obtained and analyzed on the video screen, as recorded for further analysis, too.

Intraoperative flow measurements are performed in all the perianeurysmal branches (feeding artery and branch arising from the aneurysms) with a flowmeter (Transonic Systems Inc., Ithaca, New York). The flow in the bypass is measured as well.

Surgical Decision-Making

A flow chart illustrating the possible strategies for managing complex intracranial aneurysms (IAs) is presented. On the basis of both pre-operative neuroradiological exams and intraoperative findings, one of the following treatment strategies is chosen (see flow chart in Fig. 1):

1. Direct vessel reconstruction by clipping or other (+ "protective" bypass in case of prolonged temporary occlusion)
2. Complete trapping (+ flow "replacement" revascularization). Two types of complete trapping modalities are described:
   (a) complete trapping "classic": the aneurysm is completely occluded as well as all the branches originating from the aneurysmal segment (the whole

aneurysmal arterial segment is excluded from the circulation = complete trapping).

(b) complete trapping "variant": the aneurysm is completely occluded with sacrifice of one or more, but not all, of the branches arising from the aneurysmal segment (the aneurysm and some, but not all, the branches arising from the aneurysmal segment are excluded from the circulation = complete trapping "variant").

3. Partial trapping (+ flow "replacement" revascularization): this consists of either proximal "inflow" or distal "outflow" occlusion. The aneurysm is not completely excluded from the circulation (= partial trapping).

Post-op Neuroimaging

Post-operative control angiography (CTA or DSA) is routinely executed within the first 72 h after surgery. In the case of clip reconstruction, follow-up neuroradiological exams are performed as for other clipped aneurysm patients. When the aneurysm treatment consists of complete trapping in association with bypass surgery, besides the first CTA in the first 72 h post-op, a further CTA is generally requested at 3 months to study bypass patency. In case of partial trapping, follow-up imaging studies are performed to evaluate aneurysm evolution on the basis of immediate post-op findings.

Results

Illustrative Case Series

A case series of seven patients successfully treated for complex intracranial aneurysmal lesions (location: 1 ICA, 1 ACom, 3 MCA, 2 PICA) (Figs. 2, 3, 4, 5, 6, and 7). All the patients underwent successful aneurysm treatment. All the bypasses were patent after surgery and at follow-up, and no ischemic complications have been reported. A favorable clinical outcome was achieved in all patients (modified Rankin Scale at follow-up ≤ modified Rankin Scale preoperative).

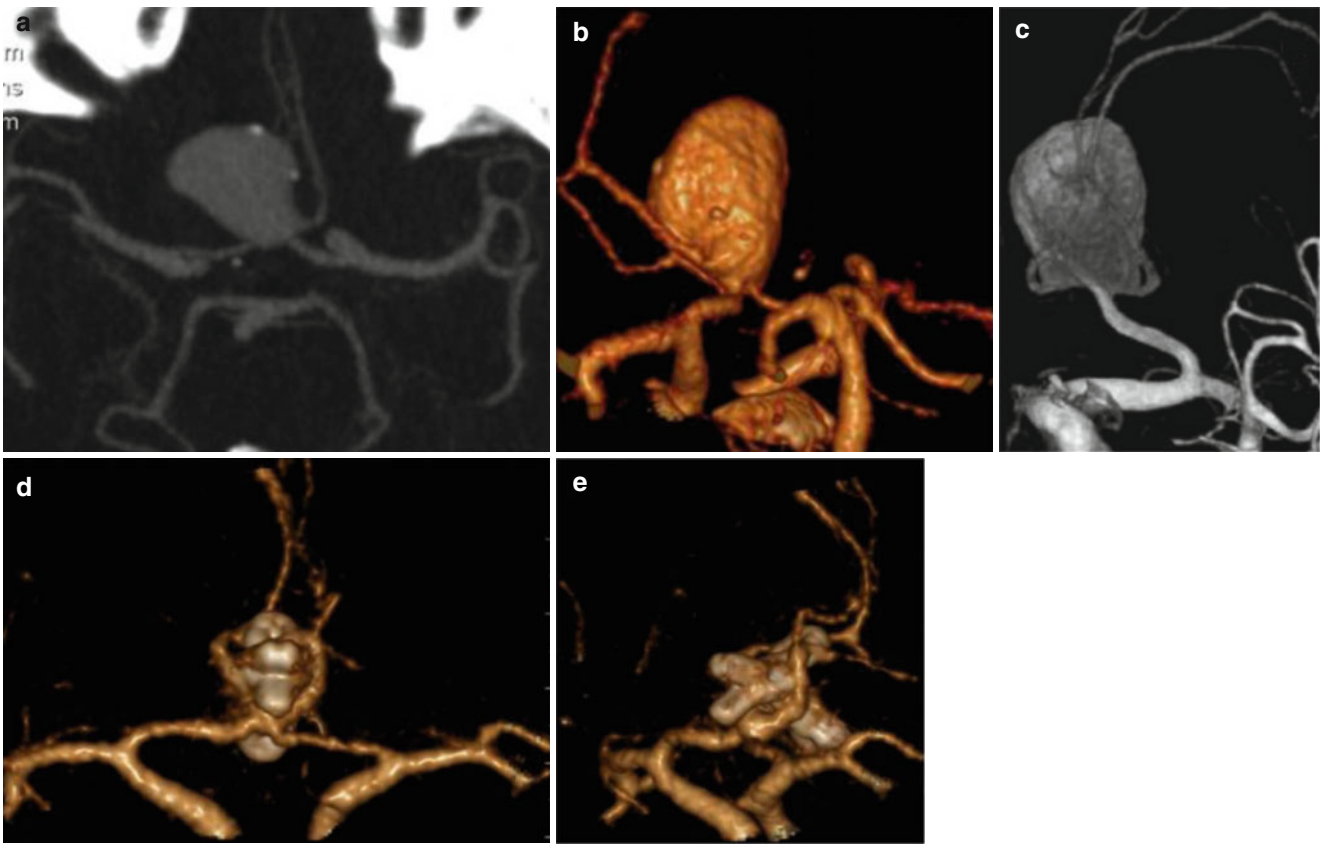

Fig. 2 Direct vessel reconstruction (by clip). Pre-operative 3D-CTA and 3D-DSA showing a ruptured giant calcified and partially thrombosed ACom aneurysm (WFNS 2) (**a–c**). Treatment consisted of thrombectomy, endarteriectomy and clip reconstruction. 3D-CTA performed 72 h after surgery documented aneurysm exclusion and patency of all the ACom complex arteries (**d**). The postoperative course was uneventful. The patient did not experienced new neurological deficit. Neurological examination after 3 weeks was without abnormalities (**e**)

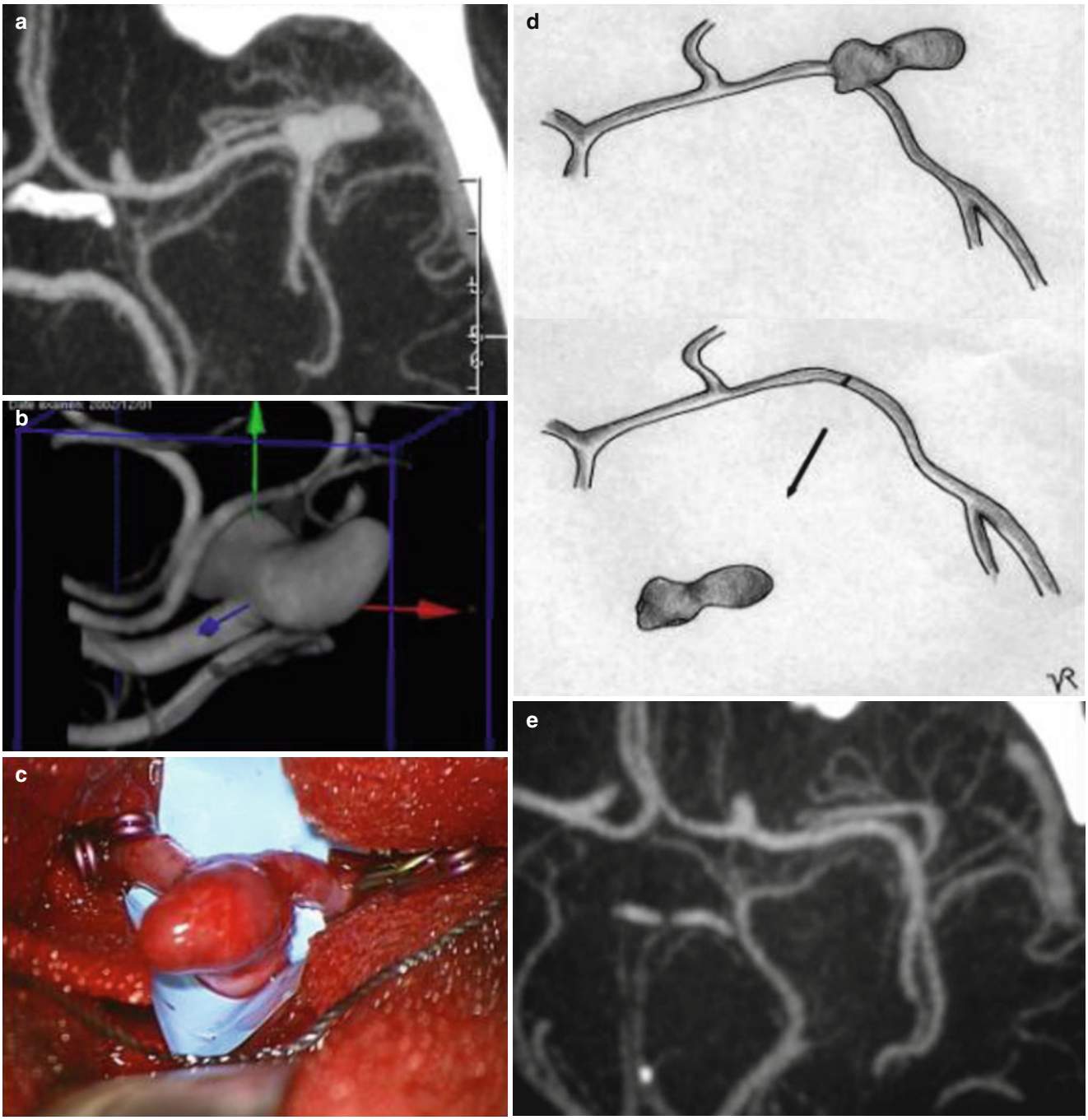

Fig. 3 Direct vessel reconstruction (by vessel re-anastomosis). Pre-operative axial CTA and 3D-DSA showing a complex ruptured aneurysm of the left MCA (WFNS 1) (**a**, **b**). Intraoperatively, after aneurysm dissection (**c**), direct vessel reconstruction was considered feasible. Therefore, the aneurysm was excised and an "end-to-end" anastomosis between the two MCA stumps was performed (**d**). Post-operative CTA showed excellent results with aneurysm disappearance and the patency of the anastomosis (**e**). The postoperative course was uneventful. The patient did not experienced new neurological deficit. Arrow indicates the removed aneurysmal segment (**d**)

Discussion

The surgical strategy for complex aneurysms is decided on the basis of pre-op neuroradiological and intra-op main determinants such as anatomical location, peri-aneurysmal angioanatomy (branch vessels, critical perforators), broad neck, intraluminal thrombosis, aneurysmal wall atherosclerotic plaques and calcifications, absence of collateral circulation, and previous treatment [2, 7]. Obviously, because the goal of any aneurysm treatment is both aneurysm exclusion and blood flow preservation [2, 3], when vessels are sacrificed or prolonged temporary occlusion is needed, cerebral

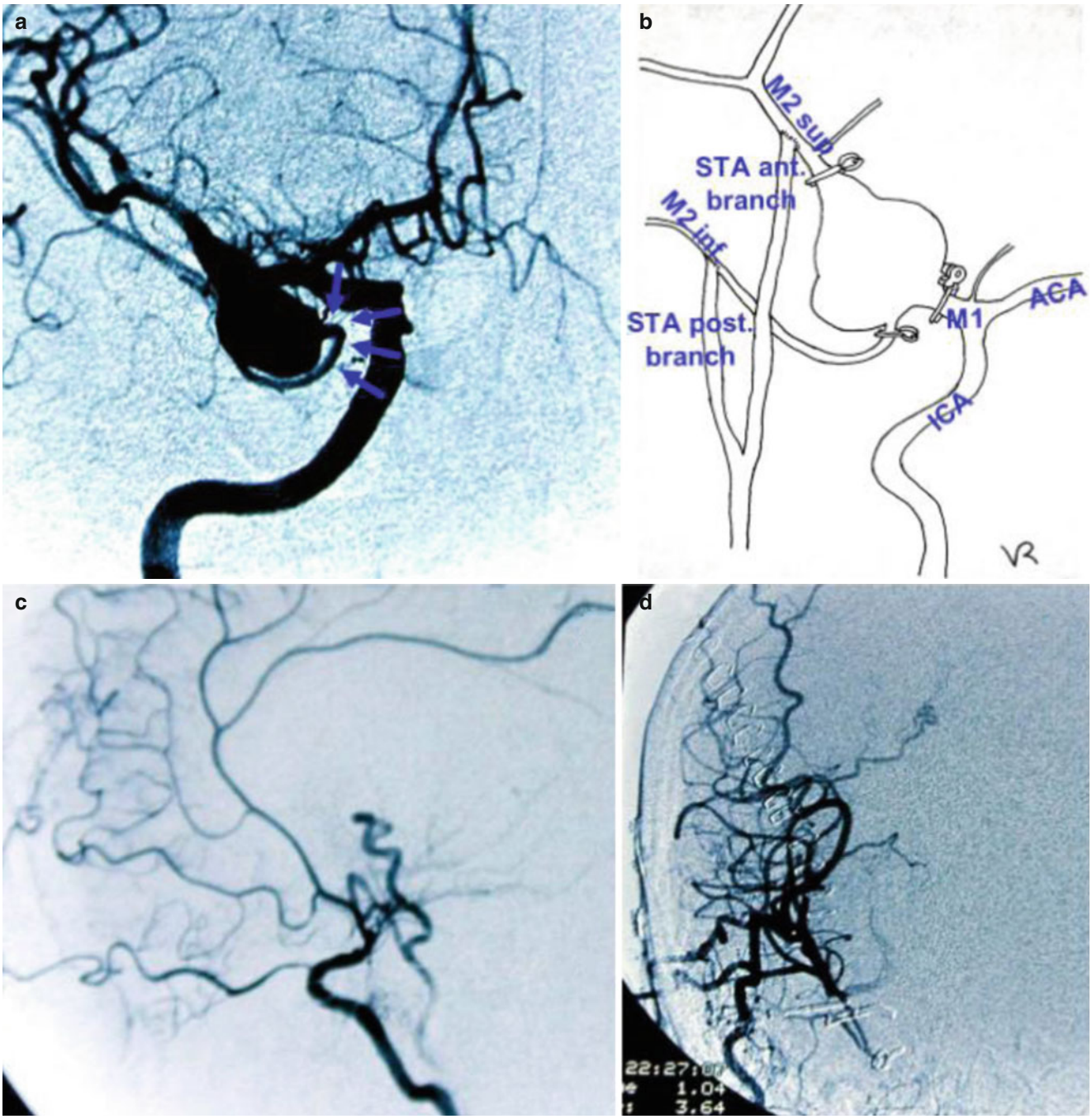

Fig. 4 Complete trapping (classic) + EC-IC bypass. Preoperative DSA showing a complex unruptured MCA aneurysm (**a**). The aneurysmal lesion was treated by complete trapping and double STA-MCA (**b**). Post-operative DSA showed aneurysm disappearance and patency of the double STA-MCA bypass (**c**, **d**). After surgery, neurological examination was normal. The postoperative course was uneventful

revascularization is an important management option [2, 4, 7–9]. The selection of the ideal bypass procedure (EC-*IC vs*. IC-IC; occlusive *vs*. non-occlusive, etc.) depends on several factors, for instance, the amount of flow to the occluded (temporary or permanently) arterial territory, the intracranial vascular angioarchitecture, the availability of donor and recipient vessels, etc. [1–3, 7].

Reconstruction of complex aneurysms by clips can be possible, for instance, after thrombectomy/ endarteriectomy in case of a giant partially thrombosed aneurysm (Fig. 2). Sometimes even direct vessel reconstruction is a valid option, depending on favorable aneurysmal angioanatomy (Fig. 3). These treatment modalities can be associated with a "protective" bypass, when prolonged temporary occlusion time is needed [9].

Trapping strategies are instead combined with the construction of a flow replacement bypass. The choice of "complete" or "partial" trapping depends on the aneurysmal and peri-aneurysmal anatomy.

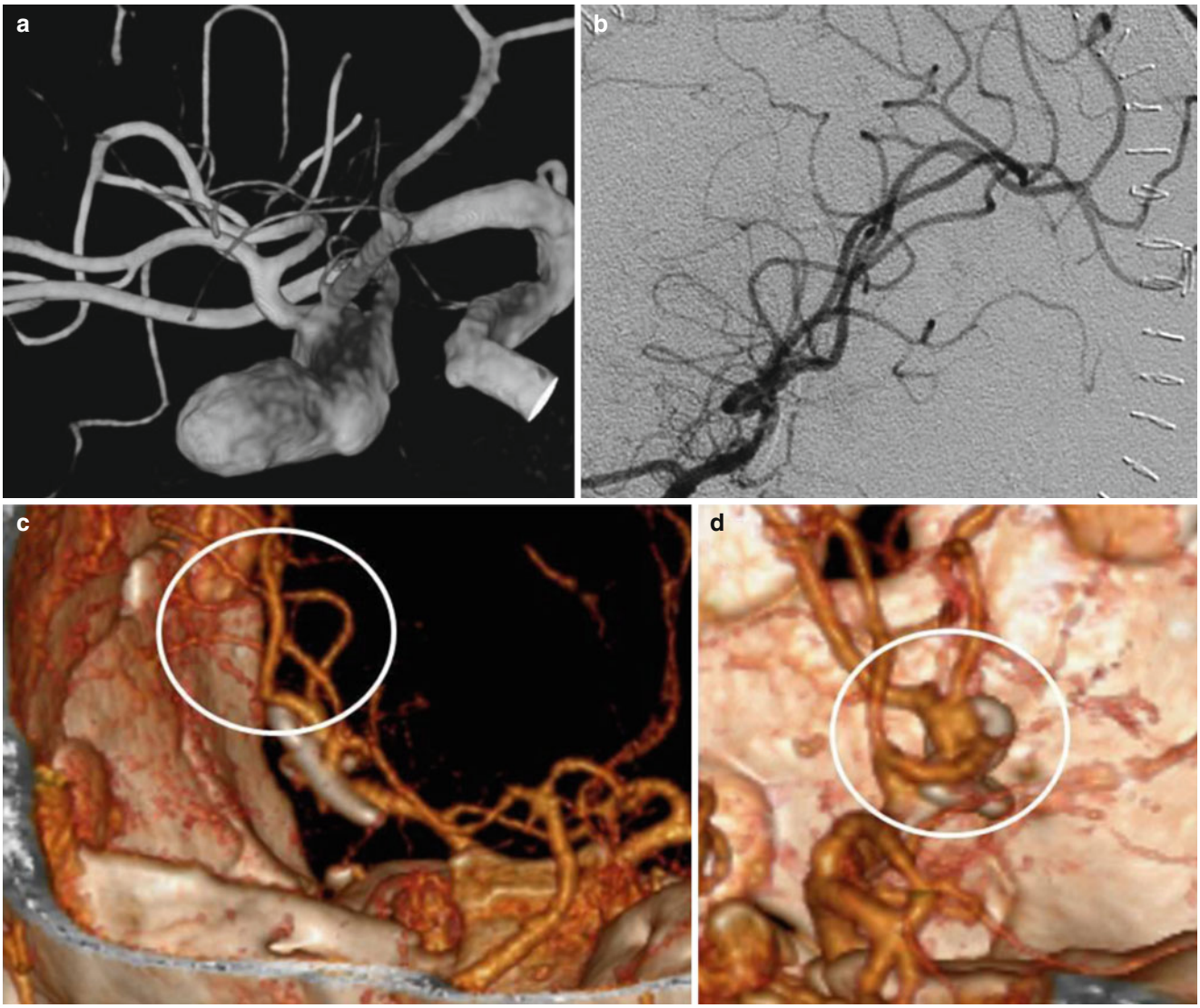

Fig. 5 Complete trapping "variant" + flow-replacement IC-IC bypass. A complex unruptured calcified and partially thrombosed aneurysms of the MCA bifurcation (pre-op DSA in **a**) has been treated by aneurysm clipping with sacrifice of the frontal M2 branch that was previously revascularized by means of intracranial-intracranial M3-M3 side-to-side anastomosis. Postoperative DSA and 3D-CTA showed aneurysm exclusion and patency of the anastomosis (**b**–**d**). The *white circles* in figure **c** and **d** indicate the side-to-side anastomosis performed. The postoperative course was uneventful

Among trapping strategies, the advantage of "complete trapping" is the immediate exclusion of the aneurysmal lesions and is the recommended option whenever feasible [3–5]. Two types of "complete trapping" strategies are herein described – the "classic" and the "variant" complete trapping. A "classic" complete trapping consists of exclusion of the aneurysm as well as the total corresponding arterial territory. Bypass surgery needs to revascularize the whole territory supplied by the artery carrying the aneurysm (Fig. 4). The "variant" trapping consists of complete aneurysm exclusion, with occlusion of one or more, but not all, branches arising from that segment. Bypass surgery needs to revascularize only a part of the territory supplied by the artery carrying the aneurysm (Fig. 5).

However, complete trapping can sometimes be hazardous, e.g., when perforating vessels arise from the aneurysm sac, or when careful inspection of every aspect of the aneurysms is considered inadvisable and risky. In these cases, partial trapping strategies represent a reasonable option, [2, 4–6, 8, 10]. Two types of partial trapping modalities are described: proximal "inflow" occlusion (Figs. 6 and 7) and distal "outflow" occlusion (Fig. 8), consisting of, respectively, occlusion

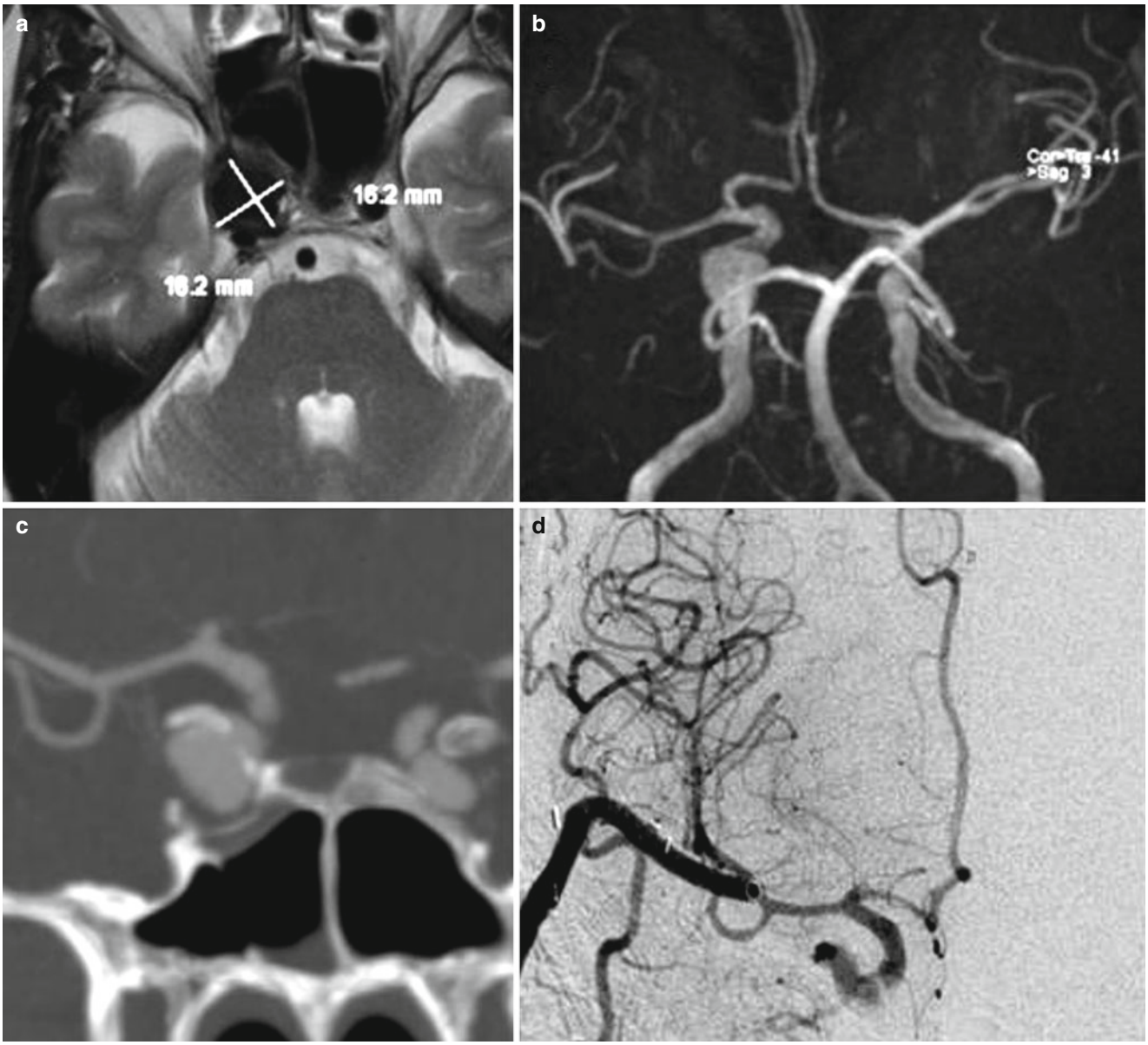

Fig. 6 Partial trapping (inflow occlusion) with EC-IC (ELANA) bypass. Pre-operative axial MRI (**a**), MRA (**b**) and CTA (**c**) showing an unruptured aneurysm of the right intracavernous ICA. The patient underwent treatment consisting of: (1) EC-IC high flow bypass performed by interposition of a saphenous vein graft between the external carotid artery and the MCA (M2 segment); (2) subsequent proximal occlusion of the cervical internal carotid artery in the neck just distal to the common carotid artery bifurcation. Postoperative DSA (**d**) showed patency of the EC-IC bypass and partial aneurysmal thrombosis. After surgery, the patient did not experience new neurological deficit. The postoperative course was uneventful. The follow-up CTA at 3 months confirmed the previous findings (partial aneurysm thrombosis and bypass patency). In this case, further neuroradiological follow-up is indicated. Note that the intracranial anastomosis has been made by the application of the Excimer Laser-assisted Non-occlusive Anastomosis (ELANA) technique, in order to avoid temporary occlusion of a proximal intracranial recipient (namely, the supraclinoidal ICA or the MCA) and subsequent risk of cerebral ischemia

before or after the aneurysmal lesion [3–8, 10]. A bypass is associated with ensuring perfusion to the territory distally to the occlusion. The rationale behind inflow and outflow occlusion is the change of flow within the aneurysmal lesion, inducing a reduction of blood flow and a decrease in hemodynamic stress. A major limitation of the partial trapping strategy remains, however, our inability to reliably predict as well as to control the amount and the speed of the thrombosis of the aneurysm. Rapid and complete thrombosis of a giant aneurysm may carry the risk of either aneurysm rupture or occlusion of the perforating arteries that one tried to preserve using partial trapping.

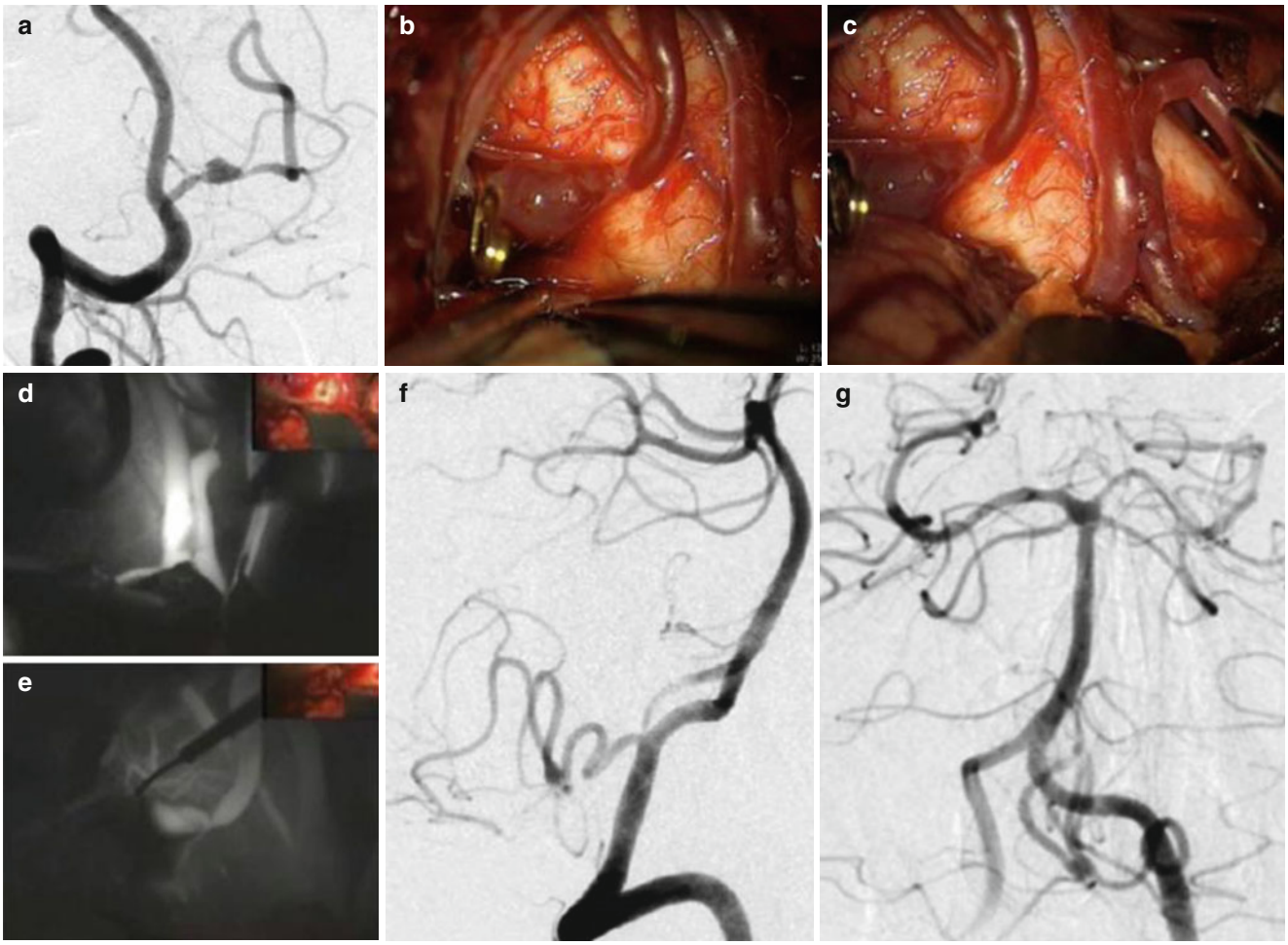

Fig. 7 Partial trapping (inflow occlusion) with IC-IC bypass. Preoperative DSA showing a dissecting ruptured posterior inferior cerebellar artery (PICA) aneurysm (HH 2, WFNS 2) (**a**). Intraoperatively the aneurysm was treated by means of side-to-side PICA-PICA anastomosis and proximal (inflow) occlusion (**b** and **c**). Intraoperative Indocyanine green videoangiography showing the patency of the side-to-side anastomosis (**d**) and the absence of fluorescence in the aneurysm (**e**). Postoperative DSA confirming patency of the anastomosis and documenting disappearance of the aneurysmal lesion (**f**, **g**). The postoperative course was uneventful. The patient was discharged after 3 weeks in good neuroligical condition. The follow-up CTA at 3 months confirmed the previous findings (aneurysm exclusion and bypass patency)

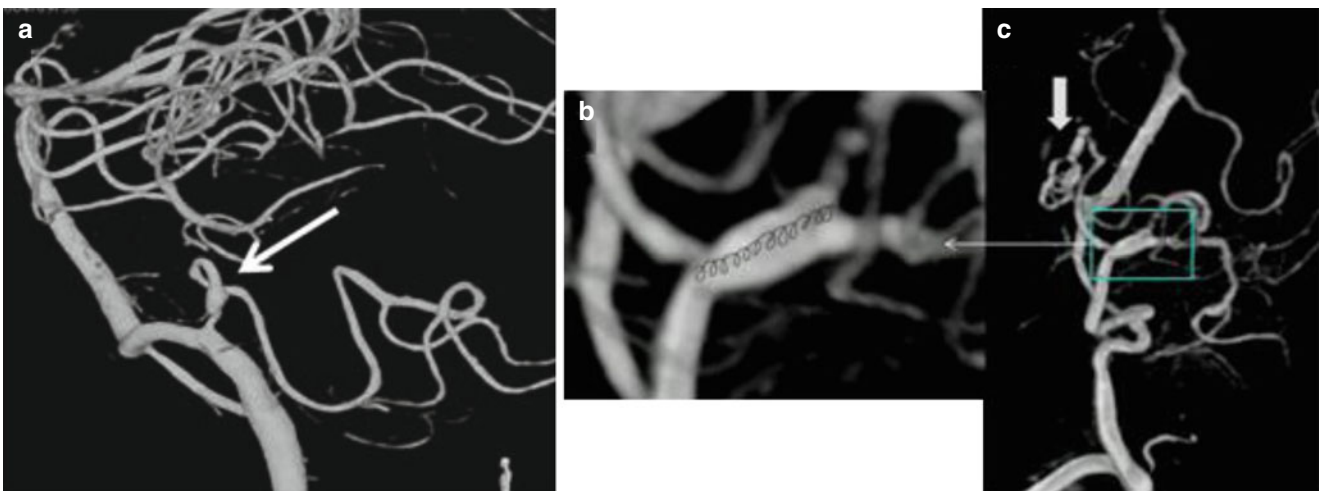

Fig. 8 Partial trapping (outflow occlusion) + IC-IC bypass. Preoperative 3D-DSA showing a dissecting unruptured aneurysm (see *white arrow*) of the posterior inferior cerebellar artery (PICA) (**a**). The aneurysm was treated by side-to-side PICA-PICA bypass and subsequent distal outflow occlusion. Postoperative DSA showed aneurysm disappearance (*white arrow* in **c**) and patency of the side-to-side anastomosis (Fig. **b** and rectangle in Fig. **c**) (**b**, **c**). After surgery, neuroligical examination was normal. The postoperative course was uneventful. The follow-up CTA at 3 months confirmed the previous findings (aneurysm exclusion and bypass patency)

Conclusions

Different various treatment modalities for managing complex intracranial aneurysmal lesions have been described herein. These strategies have been successfully applied in the management of the presented cases. Neurosurgical reference centers for cerebrovascular diseases have to be capable of offering the full spectrum of microsurgical treatment options, including revascularization procedures.

Conflict of Interest We declare that we have no conflict of interest

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Recurrent and Incompletely Treated Aneurysms

Andreas Gruber, Christian Dorfer, and Engelbert Knosp

Abstract Endovascular treatment of intracranial aneurysms has become an established technique that can provide stable permanent occlusion in over 85 % of the cases. Even those aneurysms considered untreatable by endovascular means can now often be managed by the use of adjunctive measures, e.g., balloon protection devices, intracranial stents, and semipermeable stents, i.e., "flow diverters." In those cases, in which relevant aneurysm recurrences are documented upon angiographic follow-up, both endovascular and surgical techniques can be employed. In rare cases, combined treatment strategies including parent artery occlusion under bypass protection can be performed. At our center, the majority of relevant aneurysm recurrences after initial coil embolization are managed by a second endovascular procedure. In some cases, e.g., aneurysm recurrences not feasible for endovascular re-treatment, documented aneurysmal growth, bleeding from a previously embolized aneurysm, and acute hemorrhagic or ischemic complications during endovascular procedures, surgical management may be necessary. This report briefly outlines the most frequent treatment scenarios.

Keywords Microsurgical clipping • Endovascular treatment • Parent artery occlusion • Aneurysm recurrence

Introduction

Surgical and endovascular treatment of cerebral aneurysms can be deconstructive or reconstructive in nature. Details about the therapeutic options available are given in Table 1. Among the reconstructive techniques are both microsurgical clipping and endosaccular coil embolization. Aneurysms not lending themselves to simple coil embolization can be managed by the use of adjunctive measures, e.g., balloon-assisted coil embolization [18, 20, 26], stent-protected coil embolization [1, 8], or implantation of flow-diverting devices [19, 36]. Deconstructive procedures include parent artery occlusion [PAO], PAO under bypass protection, and advanced techniques of flow modification. Altogether, both reconstructive and deconstructive procedures can be performed using either microsurgical or endovascular techniques. In either case, both safety and permanent stability of aneurysm occlusion, i.e., procedural morbidity rates and angiographic repermeation rates, are of significant importance for the quality of the aneurysm treatment.

Reconstructive endovascular treatment of intracranial aneurysms [9] has become an established technique [12, 23–25] that can provide stable permanent occlusion in up to 85 % of the cases [2, 4, 5, 37, 38]. The angiomorphology

Table 1 Techniques for the managment of intracranial aneurysms

Reconstructive techniques
Microsurgical clipping
Endosaccular coil embolisation
"Neck bridging devices"
Balloon-protected coil embolization
Stent-protected coil embolization
Flow-diverting devices
Deconstructive techniques
Parent artery occlusion [PAO]
PAO under bypass protection
Flow modification techniques

Current techniques for the treatment of intracranial aneurysms. Both microsurgical clipping and endosaccular coil embolization are reconstructive in nature. Aneurysms not lending themselves to coil embolization may be treated using neck bridging devices. Deconstructive techniques include parent artery occlusion and flow modification techniques in the presence of adequate collateral pathways. In the absence of sufficient cross flow, cerebral revascularization procedures are required to prevent cerebral ischemia

A. Gruber, MD (✉) • C. Dorfer, MD • E. Knosp, MD
Department of Neurosurgery,
Medical University Vienna, General Hospital Vienna,
Waehringer Guertel 18-20, A-1090 Vienna, Austria
e-mail: andreas.gruber@meduniwien.ac.at

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of aneurysm recurrences after initial endovascular treatment is an important parameter to distinguish unstable aneurysm residuals that are potentially prone to hemorrhage from benign non-progressing lesions and thus to identify those patients who will need further treatment. A significant number of patients with minor non-progressing aneurysm remnants is followed angiographically, and there is growing evidence indicating that these are benign lesions. In those cases in which relevant aneurysm recurrences are documented upon angiographic follow-up, both endovascular [4, 25, 31, 37] and surgical techniques [4, 10, 17, 24, 28, 33, 39, 40] can be employed. In rare cases, combined treatment strategies including, for example, PAO under bypass protection [11, 13, 15, 16, 35, 41, 42], can be performed.

Patients and Methods

We recently described our experience in the combined endovascular and surgical management of patients suffering recurrences after both surgical and endovascular aneurysm treatment [6]. All patients were managed by a team of vascular neurosurgeons who are cross-experienced in both the microsurgical and endovascular treatment of cerebral aneurysms. Indications for surgical and endovascular treatment have been reported previously [32]. Endovascular treatment of aneurysm recurrences was performed via a transfemoral approach under biplane fluoroscopy and road mapping. Aneurysm remnants of the appropriate shape were selectively catheterized and the maximum number of coils possible was delivered under systemic heparinization. Remodeling balloons and self-expandable nitinol stents served as neck bridging devices in lesions with unfeasible neck morphology.

A standard pterional craniotomy was used in the majority of aneurysms treated surgically. A unilateral anterior interhemispheric approach was used with pericallosal artery aneurysms, and supraorbital craniotomies allowing subfrontal clipping under endoscopic assistance were used in selected cases. Intraoperative angiography was routinely used, and indocyanine green (ICG) angiography was additionally performed during the last few years [27].

Unclippable aneurysm recurrences that are unfeasible for additional embolization were managed by PAO under bypass protection. In these cases, double-barrel STA-MCA low-flow bypasses were performed 48 h before endovascular balloon test occlusion [BTO] and subsequent PAO in the awake patient. In two cases of previously embolized, thrombosed, large basilar apex aneurysms, deliberate surgical basilar artery trunk occlusion was performed.

Results

As outlined in Table 2, several scenarios of insufficient aneurysm treatment are possible. Illustrative cases for these scenarios are given in Fig. 1, showing insufficient aneurysm treatment as an acute complication during the surgical or endovascular procedure [21], delayed aneurysmal hemorrhage from undetected recurrences [22], and progressive aneurysm repermeation detected upon angiographic follow-up [4, 14, 29].

Table 2 Scenarios of insufficient aneurysm therapy requiring additional treatment

Acute clinical complications			
1. EVT complication	2. Vessel occlusion	3. Surgery [coil removal]	Fig. 1a
1. EVT complication	2. Acute repeat SAH	3. Surgery [clipping]	Fig. 1b
Delayed clinical complications			
1. Uneventful EVT	2. Repeat SAH	3. 2nd EVT [coiling]	Fig. 1c
1. Uneventful EVT	2. Repeat SAH	3. Surgery [clipping]	Fig. 1d
Delayed technical complications			
1. Uneventful EVT	2. AN recurrence	3. Surgery [clipping]	Fig. 1e
1. Uneventful EVT	2. AN recurrence	3. 2nd EVT [coiling]	Fig. 1f
1. Uneventful EVT	2. AN recurrence	3. 2nd EVT [stenting]	Fig. 1g
1. Uneventful EVT	2. AN recurrence	3. Surgery [PAO + EC/IC BP]	Fig. 1h
1. Uneventful Surgery	2. AN recurrence	3. EVT	Fig. 1i

Possible scenarios of insufficient aneurysm therapy requiring additional treatment as encountered in our population. The pattern and time course of the most commonly encountered mistreatments and additional therapies is given in Table 2 [chronological sequence indicated as 1 – 2 – 3]. The corresponding illustrative cases are shown in Fig. 1 [indicated as Fig. 1a–i]

AN aneurysm, *EC/IC BP* extracranial intracranial bypass, *EVT* endovascular treatment, *PAO* parent artery occlusion, *SAH* subarachnoid hemorrhage

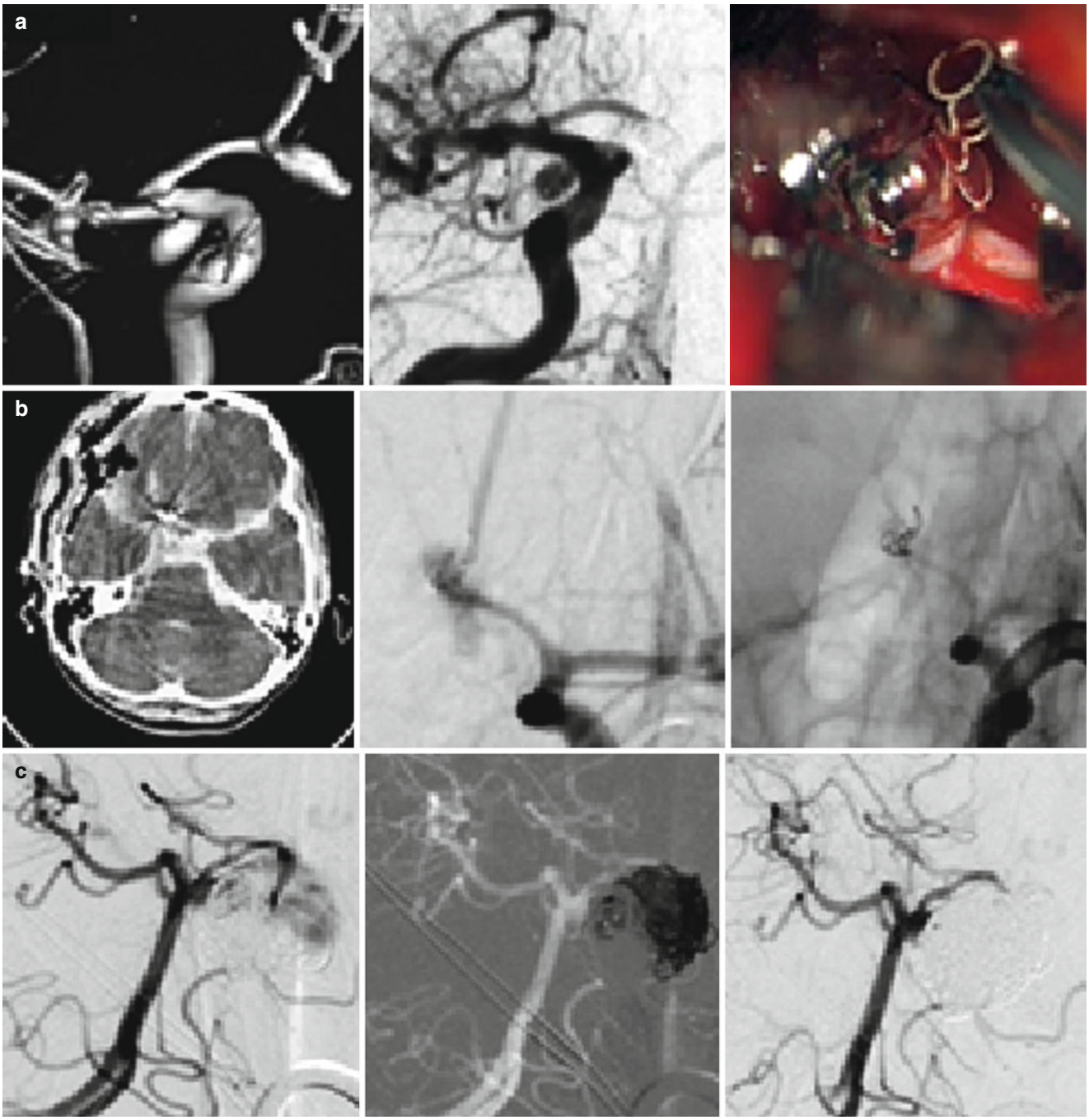

Fig. 1 Scenarios of insufficient aneurysm therapy requiring additional treatment as encountered in our population. As outlined in Table 2, (**a**, **b**) demonstrates endovascular complications managed by acute surgery, (**c**, **d**) depict delayed complications from aneurysm recurrence and repeat SAH managed by both surgery and endovascular re-intervention, and (**e**–**i**) illustrate the management of delayed aneurysm recurrences after both endovascular and surgical treatment. *ACom* anterior communicating artery, *ICA* internal carotid artery, *PAO* parent artery occlusion, *SAH* subarachnoid hemorrhage

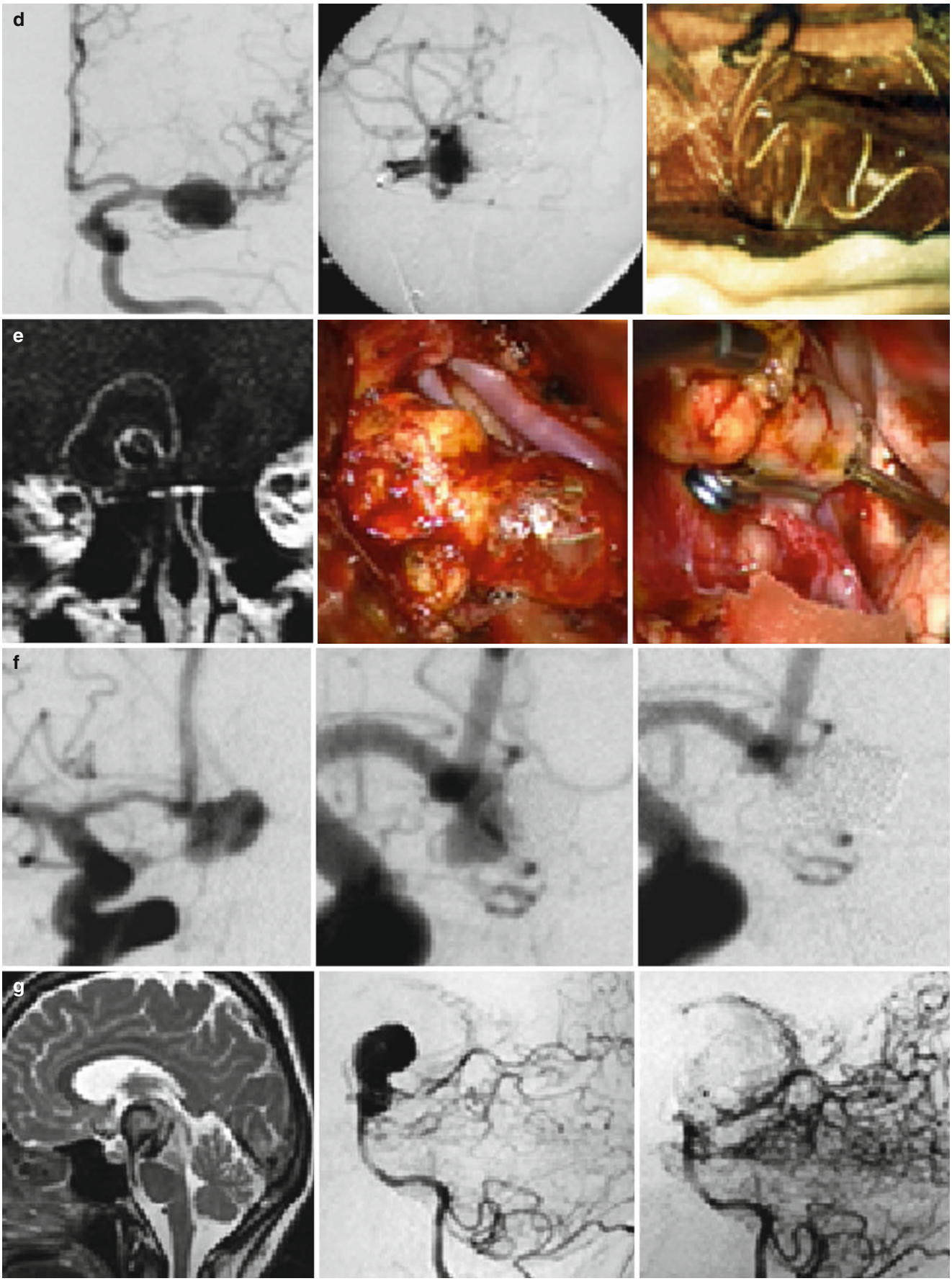

Fig. 1 (continued)

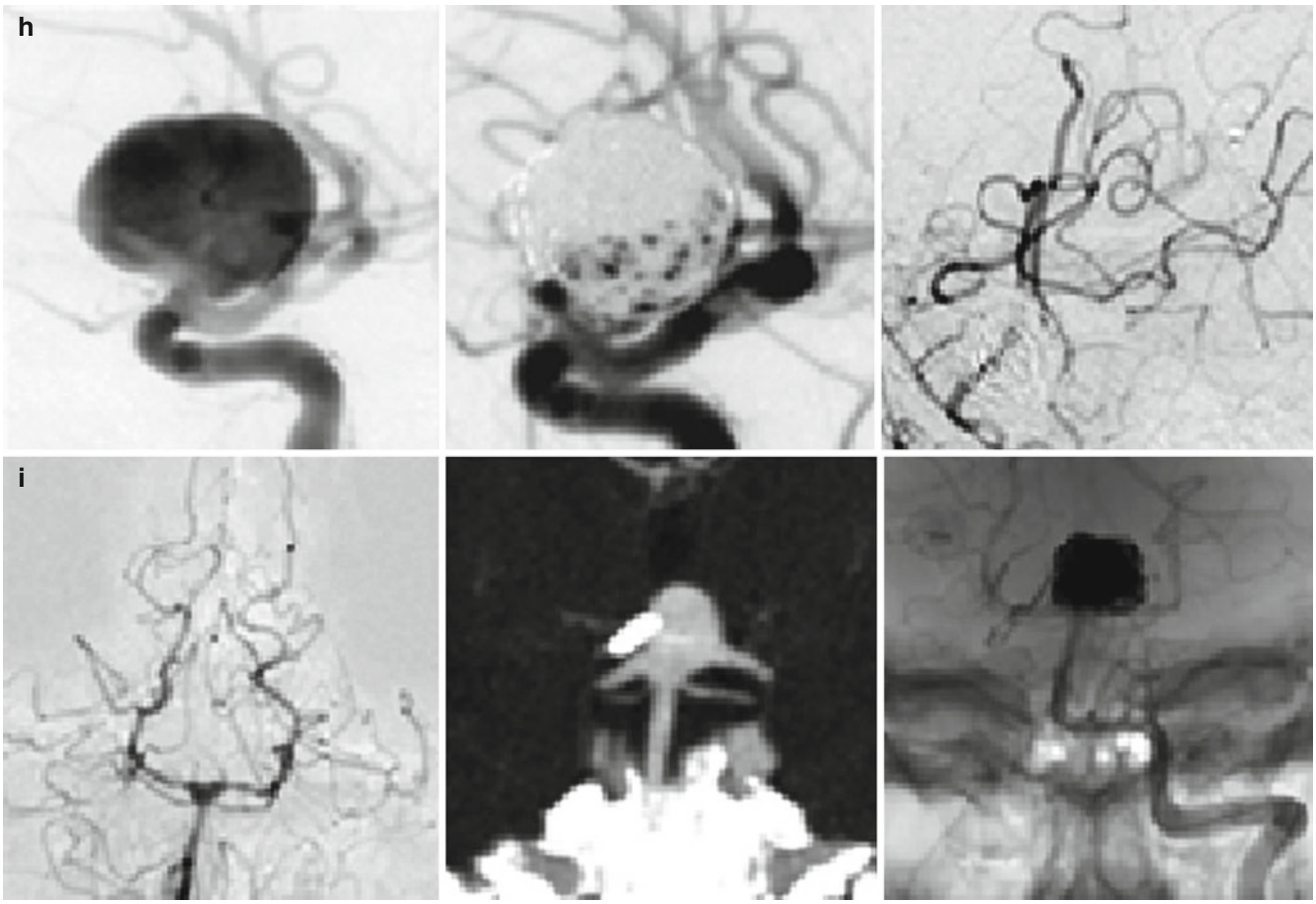

Fig. 1 (continued)

Discussion

Aneurysm size [4, 23, 31], width of the neck [29, 31, 43], treatment during the acute phase after aneurysm rupture [4, 29], initially suboptimal angiographic aneurysm occlusion [2, 4, 14, 23, 29, 31], and length of follow-up [2, 29] have been correlated with an increased risk of aneurysm recurrence. The reported rates of aneurysm recurrences after initial endovascular treatment range from 6.1 to 33.6 % [4, 14, 29], indicating the lack of consensus on the definition of relevant aneurysm re-opening. This high incidence of aneurysm residuals contrasts with the low re-intervention rate of 4.7–17.4 % [4, 5, 25, 30] and demonstrates the role of individual judgment in deciding which aneurysm residual is of sufficient concern to warrant re-treatment.

As demonstrated in Fig. 1, the problem of incomplete or unstable aneurysm occlusion is found after both surgical and endovascular treatment.

Among surgically treated patients, Feuerberg et al. [7] assessed the natural history of surgical aneurysm rests and concluded that the rebleeding risk was between 0.38 and 0.79 % per year. Advanced techniques of intraoperative monitoring, including micro-Doppler ultrasound, neuroendoscopy, ICG videoangiography [27], and intraoperative angiography have been implemented to detect incorrect clip positions and in turn reduce the misclipping rates.

In the endovascular field, Byrne et al. [2] reported a rebleeding rate of 0.4 % (1/221) for stable non-progressing aneurysmal remnants after endovascular treatment. In marked contrast, he found a 7.9 % (3/38) rebleeding rate for angiographically unstable aneurysm residuals [3]. The degree of aneurysm occlusion after treatment was strongly associated with the risk of re-rupture [14], i.e., 24.5 % (12/90) of aneurysms subtotally occluded, but only 0.8 % (2/254) of aneurysms with complete or almost complete occlusion rebled. The annual re-rupture rates after endovascular treatment reported in the literature range from 0.11 to 0.32 % [5, 23, 24, 34], with the ISAT trial reporting a 0.2 % re-hemorrhage rate for the endovascular population in the first year.

As outlined in Fig. 2, repermeation after coil embolization does not neccessarily occur by coil compaction alone. Additional mechanisms include aneurysm regrowth, migration of the coils into intra-aneurysmal thrombus, and transfundal migration of coils.

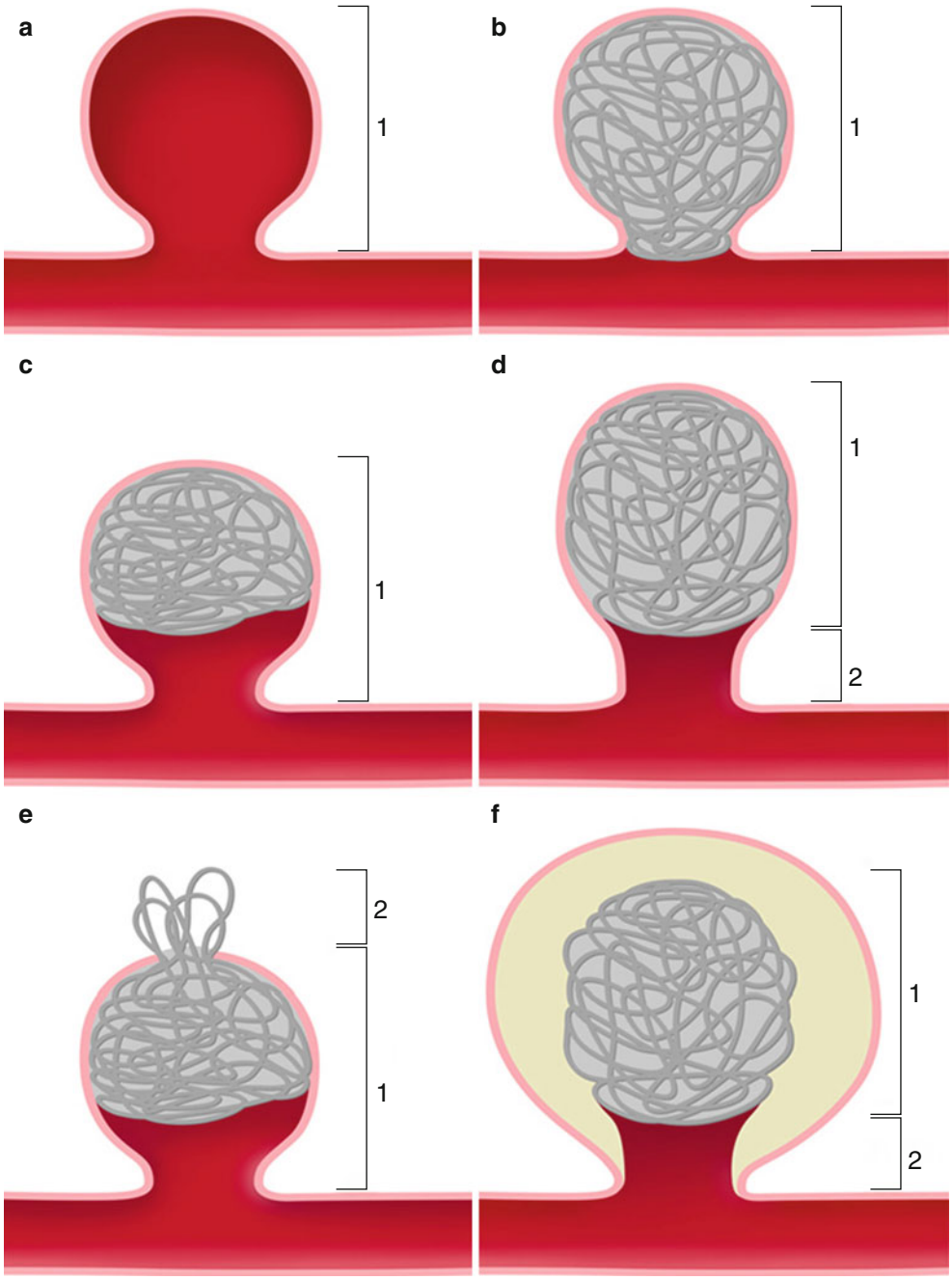

Fig. 2 Mechanisms of aneurysm recurrence after endosaccular coiling. In our population, additional treatment was considered in those cases in which (1) residual lesions were larger than 20 % of the original aneurysm, (2) there were unstable progressing neck remnants, (3) there was aneurysm growth without relevant coil compaction, or (4) the outgrowth of new aneurysmal daughter sacs were identified. Coil compaction (**c**) was identified angiographically (**a**–**c**). In cases of aneurysmal enlargement without signs of coil compaction, the aneurysm recurrence was defined as aneurysmal regrowth (**d**). Recent publications have suggested a third entity of aneurysmal recurrence, i.e., fundal migration of the coil package through the wall of the embolized aneurysmal sac (**e**). Some aneurysms operated on for angiographically suspected regrowth had a combination of regrowth and fundal migration. It is impossible to assess this mechanism beforehand, since a clear differentiation between aneurysm regrowth and coil translocation out of the aneuysmal sac – both resembling an increased fundus height angiographically – is possible during surgery only. Moreover, coil migration into intraluminal thrombus (**f**) will also simulate an increased fundus height during angiography

Conclusion

Among angiographically unstable and progressing recurrences that require additional treatment, we have recently identified and described different subsets of aneurysm recurrences that lend themselves to different treatment strategies. Aneurysm recurrences on grounds of intra-aneurysmal coil compaction without relevant changes in aneurysmal size and morphology can safely be cured by additional endovascular procedures. In contrast, recurrences on grounds of aneurysmal regrowth have a tendency to repeatedly regrow and recur in the absence of relevant coil compaction and are best managed surgically when technically feasible [6].

Conflict of Interest We declare that we have no conflict of interest.

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The Mini Supra-orbital Approach for Cerebral Aneurysm of the Anterior Portion of the Circle of Willis

Sophie Lévêque, Stéphane Derrey, Hélène Castel, and François Proust

Abstract *Objectives:* Various mini-invasive approaches have been developed over the last decade to expose the suprasellar area. The supraorbital approach takes a predominant place in exposing the suprasellar area and the Sylvian fissure.

Operative technique: Based on our surgical experience, the technique of supraorbital subfrontal approach is described in detail in this article. After an eyebrow incision, a small frontal craniotomy was performed.

Indications, advantages and limitations: This mini-invasive approach was indicated for patients with unruptured aneurysm, in patients with aneurysmal SAH without intracranial hypertension, and especially in elderly patients. This minicraniotomy (1) gave quick and direct access to the aneurysm; (2) provided less trauma of the temporal muscle and improved the cosmetic resuilts; and (3) reduced the risk of postoperative epidural hematoma thanks to the small detachment of the dura mater from the vault.

Conclusion: We concluded that this limited supraorbital approach gave adequate visualization and allows surgical manipulation within eloquent structures and can be specifically applied in absence of intracranial hypertension.

Keywords Intracranial aneurysm • Minimally invasive surgery • Supraorbital approach • Surgical technique

S. Lévêque, MD • S. Derrey, MD, PhD
Department of Neurosurgery, Rouen University Hospital,
1, Germont Street, 76031 Rouen, France

H. Castel, PhD
INSERM U982, Neuronal and Neuroendocrine Communication and Differentiation, Rouen University, Mont-Saint-Aignan, France

F. Proust, MD, PhD (✉)
Department of Neurosurgery, Rouen University Hospital,
1, Germont Street, 76031 Rouen, France

INSERM U982, Neuronal and Neuroendocrine Communication and Differentiation, Rouen University, Mont-Saint-Aignan, France
e-mail: francois.proust@chu-rouen.fr; f.proust@neurochirugie.fr

Introduction

Besides the classical Dandy's frontolateral pterional approach refined by Yasargil [21], a supraorbital approach to clip aneurysms was initially reported by Jane et al. [11]. Multiple refinements concerning this minimally invasive approach, such as removing the orbital rim [2] or incorporating into the flap the superior and lateral orbital walls [3] were published. These approaches involve the notion of keyhole surgery, a term proposed for the first time by H. Wilson [20] as a limited trephination. The concept has evolved, under the impulsion of Reich and Pernecsky et al. [16], as a geometric construction of the surgical approach with a limited craniotomy. In order to minimize the skin incision and the soft tissue dissection, an eyebrow skin incision [13, 19] was proposed as a counterpart to the frontotemporal hairline incision [18].

Various mini-invasive approaches have been developed over the last decade to expose the suprasellar area with the aim of reducing the dural opening, the brain exposure, and the brain retraction, but allowing a good visualization of the different segments of the anterior part of the Circle of Willis. The improvement of intraoperative visualization by an operative microscope and the refinement of instrumentation have allowed the evolution of these microsurgical techniques towards the mini-pterional [4, 7], mini-supra orbital [5, 8–10, 12, 17], or even trans-orbital [1, 15] approaches.

Here, we have reported methodological details on mini-supraorbital and lateral supra-orbital (LSO) approaches, which are based on our surgical experience in intracranial aneurysms.

Operative technique

The mini-supraorbital approach passes through a bone flap of approximately 3 cm in diameter, frontally located above the external half of the orbital rim with a single burr hole behind the frontozygomatic arch.

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Relevant surgical anatomy

For this mini-supraorbital approach, various surgical anatomic elements must be taken into consideration.

- The supraorbital nerves, arising from the fifth cranial nerve, were responsible for the sensitivity of the frontal scalp. All the branches, medially located between 2 and 3.2 cm from the midline of the orbital rim [6], allow starting the eyebrow skin incision at the mid-pupillary line.
- The fronto-temporal nerve of the facial nerve courses in a superficial subcutaneous tissue over the zygomatic arch approximately 1 cm in front of the superficial temporal artery. The anterior twig, to innervate the orbicularis oculi and corrugator muscles, continues 1–2 cm above the zygoma. The middle twig, to innervate the ipsilateral frontalis muscle, courses through the anterocephalad located above the galea plane [22]. During this course, the branches pass through three fat pads that separate the external fascia of the temporal muscle, and these branches may be injured during the dissection for craniotomy.
- The lateral extension of the frontal sinus must be analyzed on the preoperative CT scan in order to avoid the duro-sinusal fistulae.

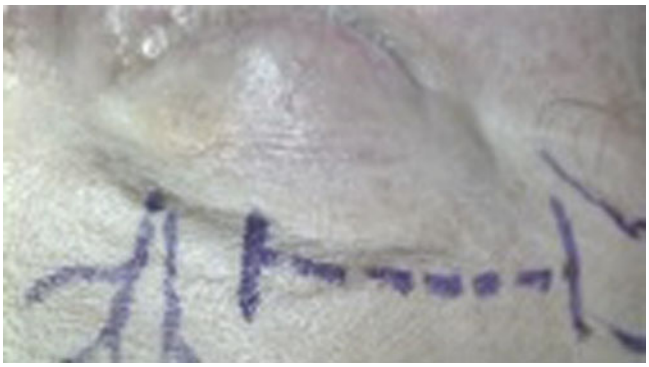

Fig. 1 Line of the right eyebrow skin incision started at the midpupillary line and extended laterally. On the left, the supraorbital nerves are represented

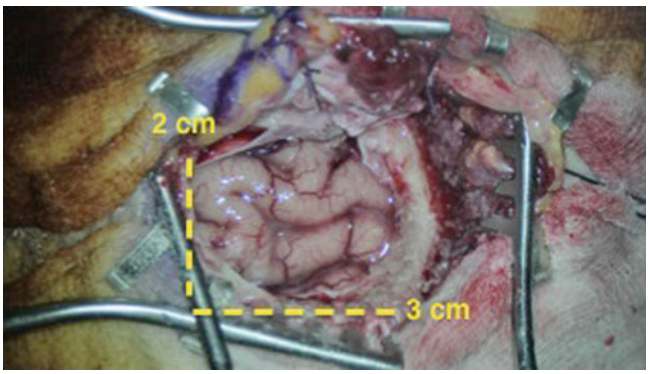

Fig. 2 After removal of the bone flap and durotomy, the frontal lobe and the cranial base are exposed

Surgical technique

The mini-supraorbital approach may pass through an incision into the eyebrow or through the fronto-temporal incision behind the hairline.

Installation. The patient is positioned in the supine position, the head on a horse-shaped holder elevated at 15°, with rotation to the side opposite the planned craniotomy (15°–20°) with a retroflexion of 20° between the plane of the anterior cranial base and the vertical axis plane.

Incision. Two procedures may be proposed: either a skin incision within the eyebrow or the fronto-temporal incision behind the hairline.

The eyebrow skin incision started at the midpupillary line and extended laterally for 4–5 cm up to the fronto-zygomatic arch (Fig. 1). This last incision respected the superficial frontal arteries and the fronto-temporal branches of the facial nerve that did not cross the surgical field. A large frontal galeal flap was tilted forward. The temporal muscle is stripped from its bony insertion to display the curve of the fronto-zygomatic junction.

The fronto-temporal incision behind the hairline allowed forward tilting of the frontal scalp, being very careful at the proximal part of the temporal muscle. The frontal galea may be tilted up to the orbital rim and the temporal muscle incised at a distance from the temporal line was pushed according to an arciform incision up to the Sylvian fissure.

Craniotomy. The burr hole (single) under the temporal muscle was made at the point of contact with the zygomatic arch. A high speed craniotome determined a straight cutline parallel to the orbital rim from the lateral to the medial position, taking into account the lateral border of the frontal paranasal sinus. A superior c-shaped line-up to the initial hole cut out a small bone flap of 3 cm wide and 2 cm high.

I*ntracranial steps*. The opening dura is made in a curved fashion with its base at the cranial base (Fig. 2). The brain relaxation was patiently obtained by suction of the cerebrospinal fluid (CSF) after opening the chiasmatic and carotid cisterns or the Sylvian fissure. Self-retaining spatulas were used as brain protectors rather than brain retractors. This approach provided, with the help of several cotton balls placed laterally, a correct visualization of the anterior communicating artery complex and the supraclinoid carotid artery area (Fig. 3). With correct brain relaxation, we could open the Sylvian fissure without trauma to the frontal lobe and reach the principal aneurysm location on the middle cerebral artery.

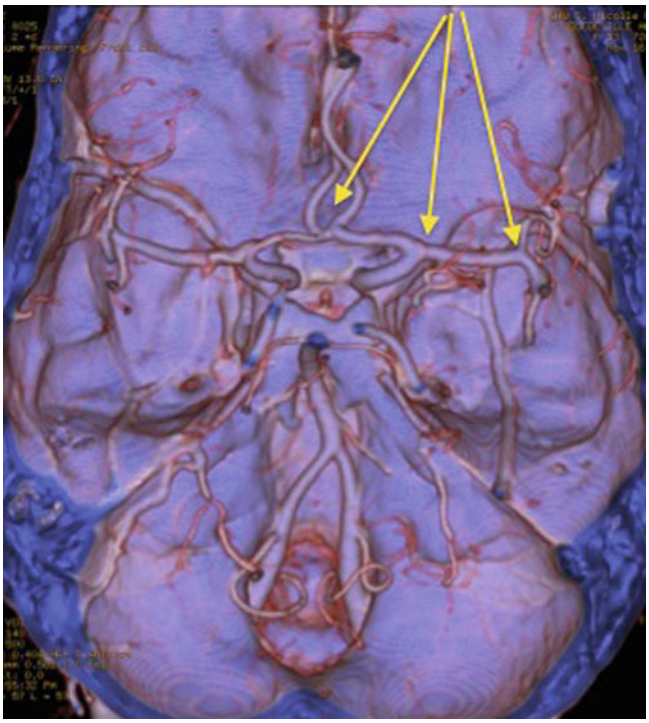

Fig. 3 An angioscanner shows the anterior part of the Circle of Willis and the *arrows* give the optical view from the mini supraorbital approach to the principal location of intracranial aneurysms

Dural closure and bone flap reconstruction. After aneurysm clipping, the dura mater is closed in a watertight fashion with repair of all defects. The bone flap is replaced and fixed with craniofix©. An autologous osseous graft is interposed between the borders of the craniotomy and the bone flap, recovered by the frontal galeal flap. The temporal muscle is suspended to the zygomatic arch and the skin closed with a subdermal resorbable suture.

Indications, advantages and limitations

This mini-invasive approach is indicated for patients with an unruptured aneurysm, for patients with aneurysmal subarachnoid hemorrhage (SAH) without intracranial hypertension, and especially for elderly patients. In those over age 70, the absence of intracranial hypertension related to the frequent cortical atrophy combined with the reduced operating time favored this approach. The choice of the side was determined by the prediction of the easiest clip application. For an aneurysm on the major bifurcation of the middle cerebral artery, we must take into consideration the relationship between the middle cerebral artery and the sphenoidal wing as well as the length of the M1 segment.

Advantages

This minicraniotomy gives quick and direct access to the aneurysm, reducing the time of the operation [14]. The reduced trauma to the temporal muscle eases the cosmetic reconstruction. The small detachment of the dura mater from the vault decreases the risk of postoperative epidural intracranial hematoma [2, 10, 16]. Moreover, a ventricular drainage through the keyhole is possible. The cosmetic results are excellent after replacement of the bone flap by craniofix® and interposition of osseous bone auto graft into the continuity solution between the bone flap and the osseous vault.

Limitations

The volume of the surgical exposure is smaller than the pterional approach [7, 8]. The intracranial hypertension, whether caused by intraparenchymatous hematoma or cerebral edema, is a formal contraindication to performing this approach. A small craniotomy may cause hinging of the herniating brain against the bone margin. The ventricular catheter may be difficult to put in the frontal horn of the lateral ventricle. In cases of intraoperative rupture of aneurysm, the habit and the control by succor is a key to the success.

How to avoid complications and specific perioperative considerations

Astute patient selection remains the major key point. A perfect preoperative analysis of clinical and iconographic characteristics should allow to better define the most appropriate surgical indications. The absence of intracranial hypertension is the first argument for indication for this procedure. The exposure of the zygomatic arch is crucial to cutting off the flap just at the point of contact with the orbital rim. The second point is to obtain proper brain relaxation before starting the aneurysm dissection. In the case of vascular rupture, it is recommended to never take off the succor in order to control bleeding and to avoid the collection of blood under the brain that is responsible for cerebral hernia.

On the preoperative imaging (cerebral angioscanner and/or cerebral angiography), various points must be checked:

- The aneurysm morphology and projections
- The symmetry analysis of the anterior communicating artery complex
- The lateral extension of the frontal paranasal sinus
- The length of M1 segment
- The relationship between the sphenoidal wing and the major bifurcation of the MCA

Conclusion

This minicraniotomy through the eyebrow gives direct and quick access to the anterior part of the Circle of Willis. In the absence of intracranial hypertension, this approach may be proposed for microsurgical exclusion of aneurysms, respecting the supraorbital nerves and performing a single burr hole at the point of contact with the zygomatic arch. We conclude that this limited supraorbital approach gives adequate visualization and allows surgical manipulation within eloquent structures.

Conflict of Interest We declare that we have no conflict of interest.

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Surgical Exclusion of Unruptured Middle Cerebral Artery Aneurysms: Experience of 126 Cases

A. Pasqualin, P. Meneghelli, F. Cozzi, and A. Giammarusti

Abstract A group of 126 surgical patients with 143 unruptured MCA aneurysms was evaluated in order to determine the risks of treatment and possible adjuncts for safer surgery. The precise location and size of the aneurysms were determined in each case; 21 aneurysms were located on the M1 tract, 109 on the main division – which consisted of more than two branches in 10 cases and was proximally located in 12 cases – and 13 were distal; 36 aneurysms were small (<7 mm), 90 standard, and 17 large or giant (>15 mm); 45 patients harbored multiple aneurysms (12 on the ipsilateral MCA). The aneurysms were excluded by clip in most cases, with the assistance of intraoperative flowmetry in 78 patients. Temporary proximal vessel occlusion was used in 57 patients (>10 min in 8 cases), without significant effects on radiological or clinical outcome. After surgery, newly occurring minor deficits were observed in 5 patients and significant deficits in 4; one patient died from an intractable coagulopathy. The low rate (3.9 %) of unfavorable results (modified Rankin Score > 2) linked to surgery justifies serious consideration for treatment in these patients, especially when facing the high disability rate after the rupture of aneurysms in this anatomical location.

Keywords Middle cerebral artery • Unruptured aneurysms • Microsurgery • Intraoperative flowmetry • Temporary vessel occlusion

Introduction

The treatment of unruptured cerebral aneurysms remains a matter of controversy; despite many studies evaluating the natural course of these lesions [11, 18, 19, 23, 24] the precise risk of rupture each year is not known, owing to many variables such as aneurysmal size, morphology of the sac, proportion between neck (or diameter of afferent vessel) and depth of the sac, and more [6, 7, 13, 22]. Also, the location of the aneurysm may be associated with a higher (or lower) propensity for bleeding, and the middle cerebral artery (MCA) seems a less risky location [19]. Thus, indications for surgical treatment of unruptured MCA aneurysms have not yet received wide approval in the neurosurgery community, considering as well the possible treatment-related morbidity connected with this location.

The aim of this paper is to review the experience of our center in surgery on unruptured MCA aneurysms in order to clarify the risks of surgical treatment and to point out some intraoperative adjuncts possibly leading to safer treatment and decreased morbidity.

Materials and Methods

From 1991 to 2011, 289 patients with unruptured cerebral aneurysms underwent surgery in our center; of these, 126 (44 %) were operated on for aneurysms located on the middle cerebral artery.

There were 43 males (34 %) and 83 females (66 %); the mean age at surgery was 55.6 (ranging from 26 to 75 years). Of the 126 patients treated, 18 (14 %) had experienced a previous hemorrhage from another aneurysm. All patients were carefully assessed with pre-operative angiography in order to define the precise aneurysmal location, MCA division anomalies, aneurysmal diameter, and presence of multiple aneurysms. As regards aneurysmal location, 21 aneurysms (15 %) were located on the M1 tract, 109 aneurysms (76 %) on the main MCA division, and 13 aneurysms (9 %) distal to the main MCA division (with 11 of these adjacent to the main division). The MCA division was proximally located in 12 cases, and a tri- or tetrafurcation was reported in 10 cases

A. Pasqualin (✉) • P. Meneghelli • F. Cozzi • A. Giammarusti
Institute of Neurosurgery and Section of Vascular Neurosurgery, Verona City Hospital, Via Milazzo, 2, Verona 37128, Italy
e-mail: albertopasqualin@tin.it

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(Fig. 1); aneurysmal size was <7 mm in 36 cases (25 %), 7–15 mm in 90 cases (63 %) and >15 mm in 17 cases (12 %); of these, 4 aneurysms were over 20 mm. Forty-five patients (36 %) showed multiple aneurysms (Figs. 2 and 3) (with a total of 143 MCA aneurysms treated); 12 patients (9 %) harbored multiple aneurysms on ipsilateral MCA (Fig. 2) (5 patients only on ipsilateral MCA) (Fig. 3).

One hundred and twenty-four patients underwent aneurysm exclusion by clip; in 2 patients, only a wrapping was performed. During surgery, intraoperative flowmetry was applied in order to avoid inadvertent occlusion or stenosis of parent vessels, and temporary proximal vessel occlusion was used in order to obtain a safer manipulation of the aneurysm before the positioning of a definitive clip. On the whole, an intraoperative measurement of flow was obtained in 78 patients; the mean flow recorded (± SD) was 39.2 ± 16.0 ml/min on the M1 tract, 21.0 ± 10.6 ml/min on the M2 branches, and 13.5 ± 5.6 ml/min on the M3 branches. As regards temporary occlusion, this was divided into two modalities – intermittent and continuous – according to a previous classification of our group [8]. A total of 57 patients underwent temporary occlusion, which was continuous in

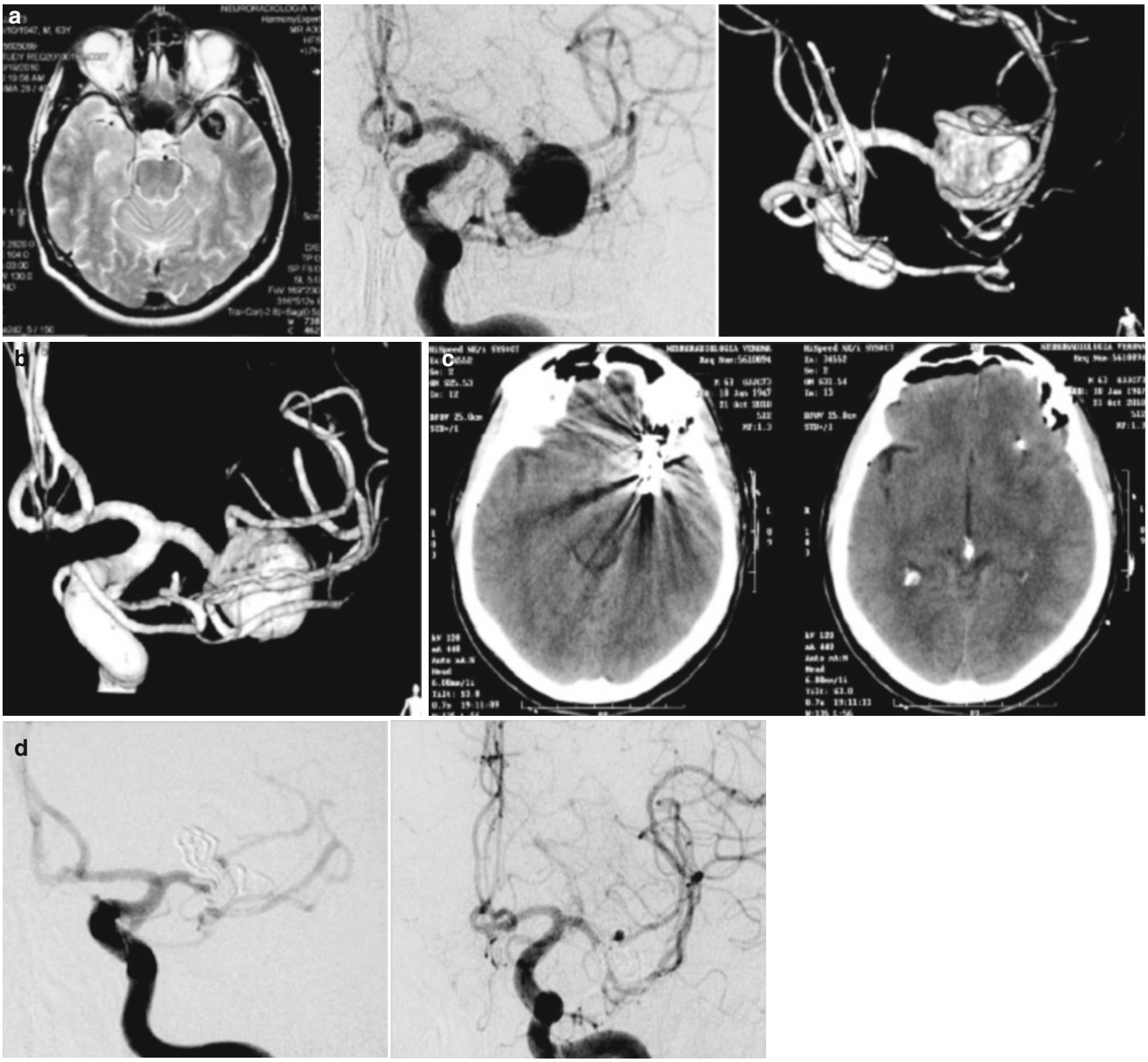

Fig. 1 A 63-year-old woman with vertigo: (**a**) MRI discovery of a large (18 mm) MCA aneurysm; (**b**) pre-operative angiography showing a large aneurysm on the MCA trifurcation (1 frontal and 2 temporal branches); (**c**) post-operative CT scan; (**d**) post-operative angiography showing complete exclusion of the aneurysms with multiple clips. Upon discharge, the patient showed a transient hemiparesis (36 h), without deficits

34 patients (59 %) and intermittent in 23 (41 %), with a total of 8 occlusions lasting ≥ 10 min (Table 1). All patients underwent post-operative angiography in order to confirm the complete obliteration of the aneurysm.

The clinical outcome was evaluated at 6 months according to the modified Rankin Scale (mRS), and a statistical analysis was done using the chi-square test and the Fisher exact test if the sample size was too small.

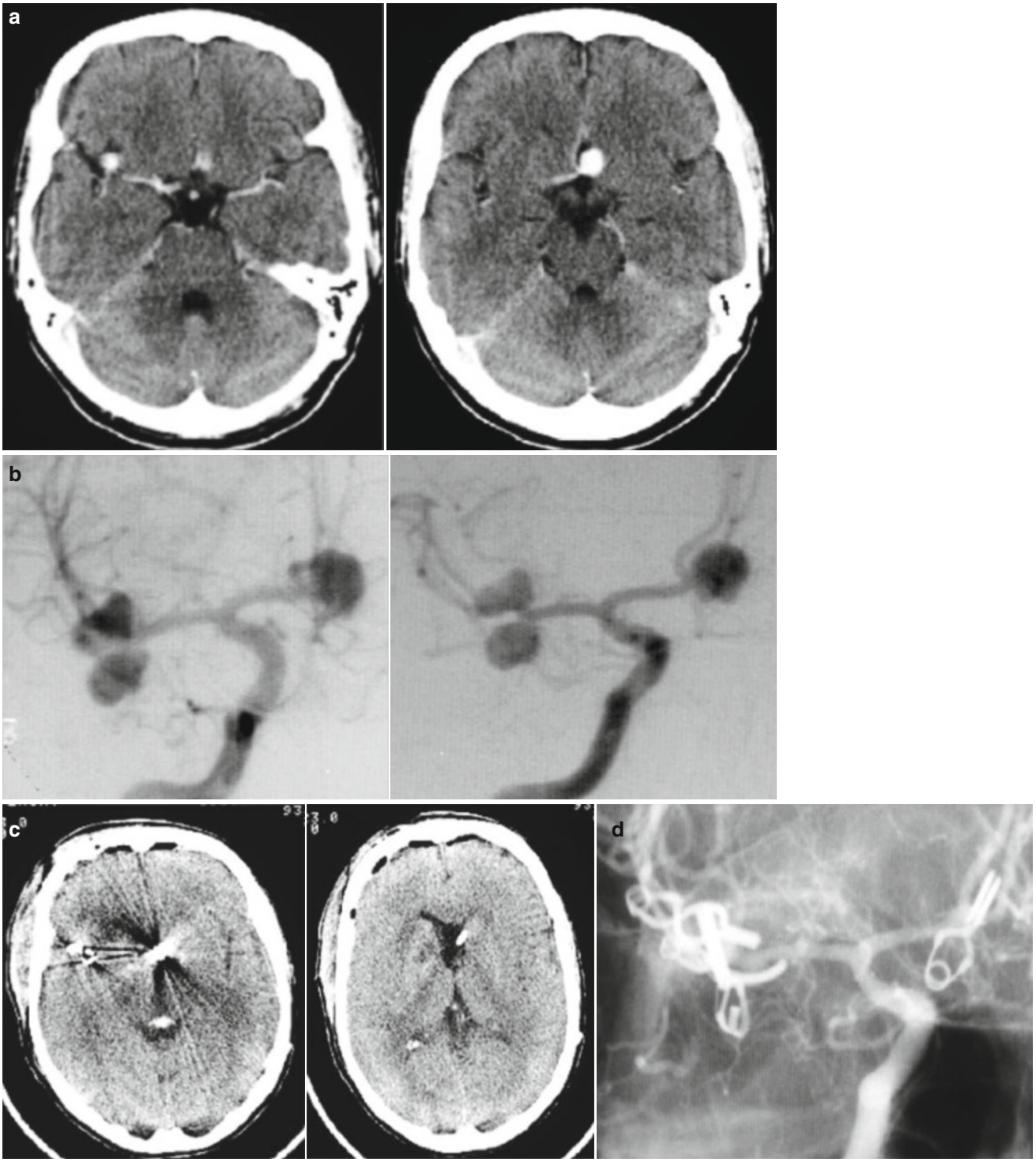

Fig. 2 A 39-year-old woman submitted to VP shunt 11 years earlier: (**a**) CT scan with evidence of multiple aneurysms; (**b**) pre-operative angiography, showing two MCA aneurysms and an ACoA aneurysm; (**c**) post-operative CT scan after exclusion of all aneurysms in one stage; (**d**) post-operative angiography showing complete exclusion of all aneurysms. Upon discharge, the patient showed transient confusion in the post-operative period, without deficits

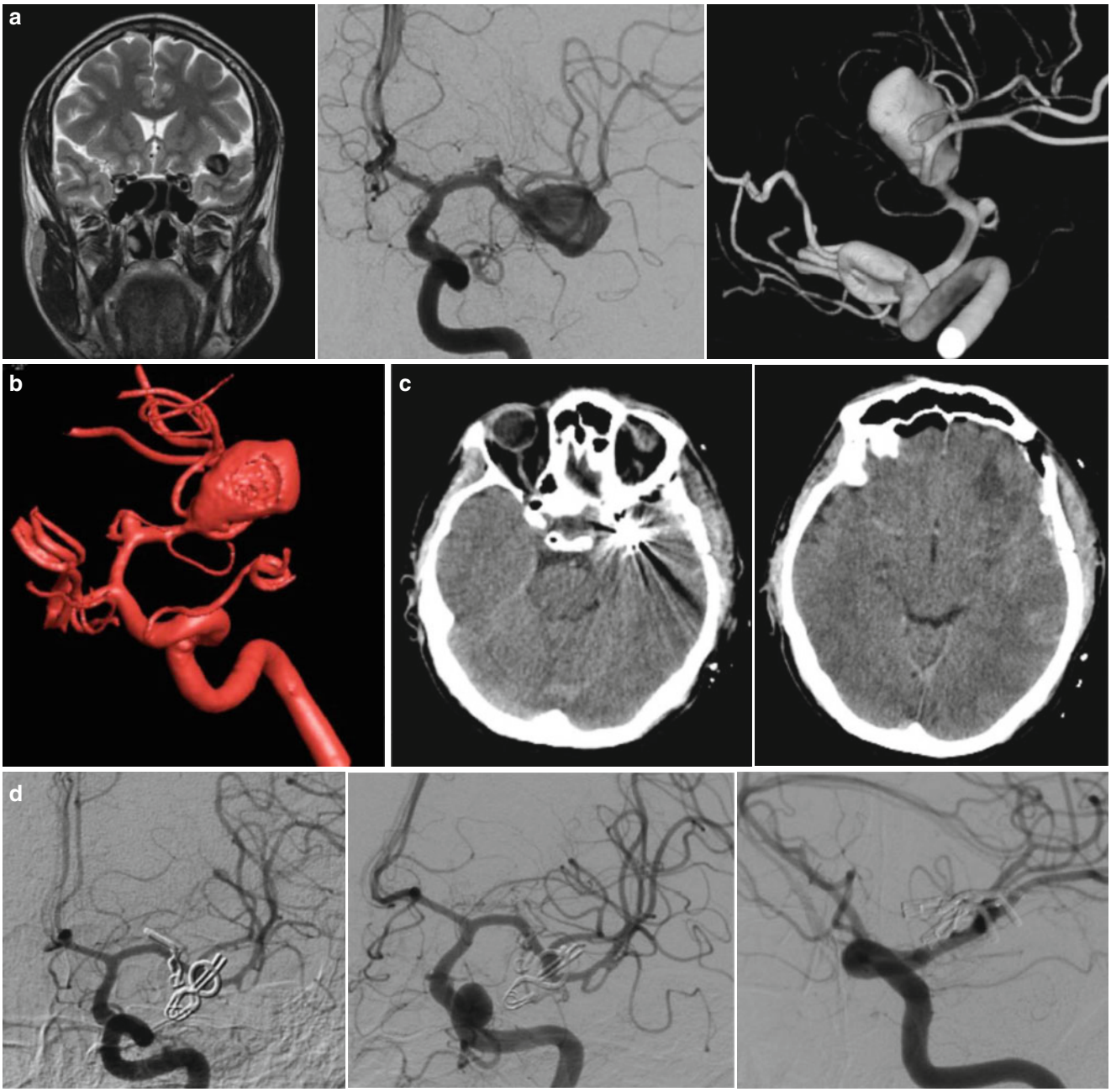

Fig. 3 A 55-year-old man with headache and family history of aneurysms: (**a**) MR coronal T2 weighted image showing a large MCA aneurysm; (**b**) pre-operative angiography with 3D reconstruction, showing a large (18 mm) aneurysm of left MCA division and a small aneurysm on the ipsilateral M1 tract; (**c**) post-operative CT scan; (**d**) post-operative angiography, showing complete exclusion of the aneurysms. The patient did not show post-operative deficits

Table 1 Temporary clipping (57 patients): occlusion period versus modality of afferent vessel occlusion

	Occlusion modality		Total
	Continuous	Intermittent	
<5 min	18 (31 %)	5 (9 %)	23 (40 %)
5–9 min	14 (25 %)	12 (21 %)	26 (46 %)
≥10 min	2 (3 %)	6 (11 %)	8 (14 %)

Results

Following surgery, neurological deficits were reported in 5 patients (8 %) out of the 57 who underwent temporary vessel occlusion (Table 2); of these, 2 experienced a transient deficit, while 3 patients experienced a permanent deficit, with hemianopsia in 1 case and hemiparesis in 2 cases;

in three of the patients with a permanent deficit, occlusion of an efferent vessel was demonstrated on post-operative angiography. Hemorrhage due to reperfusion was seen in 3 patients (5 %) – in 2 cases (with hemorrhage size ≈ 1 cm) without symptoms and in 1 case (with hemorrhage ≈ 2.5 cm) with transient symptoms (Table 2). On the whole, 49 patients were subjected to temporary occlusion for <10 min, and of these, 2 (4 %) experienced symptomatic stroke; conversely, 8 patients were subjected to temporary occlusion for ≥10 min and 3 of them (37 %) experienced a symptomatic stroke. Therefore, the duration of occlusion ≥10 min carries a significantly higher risk of symptomatic stroke ($p = 0.01$).

During intraoperative flowmetry, the following was seen in a small number of patients: (1) redistribution of flow on the MCA division branches, with significant decrease in the flow in one branch (generally in the temporal one) and an increase in the other branch; and (2) post-occlusive hyperemia on M1 tract and M2 branches after temporary clipping, with an average two-fold increase of flow immediately after removal of the temporary clip.

The clinical outcome is shown in Table 3. Of the 126 patients operated on for unruptured MCA aneurysm, 115 did not show pre-existing neurological deficits; in this subgroup, 8 (7 %) showed post-operative disability, which was severe (mRS > 3) in 4 cases (3.5 %); one patient died due to severe coagulopathy. In the group of patients with pre-existing deficits (11 cases), 7 (64 %) showed a moderate disability, and 4 (36 %) a significant disability after surgery. In patients without pre-existing deficits, the clinical outcome was also related to the size of the aneurysm (Table 4); on the whole, an unfavorable result was reported in 3 cases (3.1 %), with small or standard-size aneurysms, and in 2 cases (11.7 %) with large or giant aneurysms.

Table 2 Temporary clipping (57 patients): relation between temporary occlusion and post-operative morbidity

	Transient deficit	Permanent deficit
Ischemic symptoms (5 cases)	2 (occlusion times 5 and 12 min)	3[a] (occlusion times 7, 19, 21 min)
Hemorrhage due to reperfusion (3 cases)	1 (occlusion time 9 min)	–

[a]All with permanent occlusion of efferent vessel

Discussion

Middle cerebral artery aneurysms account for the majority of unruptured aneurysms discovered after the MRIs began to be used as a diagnostic tool; on the other hand, the middle cerebral artery location is a less common site for aneurysmal rupture than the anterior communicating artery. This observation has led to the belief that the natural risk of hemorrhage for incidentally discovered aneurysms is lowest for this location; in some groups, it is calculated to be less than 1 % for an aneurysm of standard size [19, 23, 24]. Despite this apparently benign natural course, the rupture of an aneurysm located on the middle cerebral artery is associated with a high incidence of intraparenchymal hematomas [14, 15] and with an unfavorable course in many cases, due to the morbidity caused by the devastating effects of bleeding; moreover, it is a common observation that large hematomas can be caused also by small (< 7 mm) aneurysms of the MCA. The efficacy of endovascular techniques for aneurysm exclusion has not yet been proved for this location [1, 10, 17], due to anatomical features (such as a relatively large neck and problematic morphology of the MCA division) [16] that constitute an obstacle to adequate coiling of the sac and threaten perviety of efferent vessels.

Table 3 Clinical outcome (modified Rankin scale) according to clinical presentation

	mRS					
Presentation	0	1	2	3	4	Death
No deficit (115 cases)	106 (92 %)	4 (3.5 %)	–	2 (1.8 %)	2 (1.8 %)	1[a] (0.9 %)
Pre-existing disability (11 cases)	–	6 (54 %)	1 (9 %)	1 (9 %)	3 (28 %)	–
Total (126 cases)	106 (84 %)	10 (8 %)	1 (0.8 %)	3 (2.2 %)	5 (4.2 %)	1[a] (0,8 %)

[a]Death due to severe coagulopathy

Table 4 Clinical outcome (modified Rankin scale) according to aneurysmal size, in 115 patients without pre-existing disability

	Unfavorable results			
Size	mRS 3	mRS 4	death	Total
Small – Standard ≤ 15 mm (98 cases)	2[a] (2 %)	–	1[b] (1.1 %)	3 (3.1 %)
Large – Giant > 15 mm (17 cases)	–	2 (11.7 %)	–	2 (11.7 %)

[a]One case due to ischemia after clipping of associated pericallosal aneurysm
[b]Death due to severe coagulopathy

Considering all the above-mentioned points, through this study we have tried to understand whether a direct microsurgical exclusion – aided by intraoperative flowmetry and a wider use of temporary vessel occlusion – can constitute a safe approach for the treatment of unruptured aneurysms in this location; if this proves to be true, the indication for treatment can be widened, thus preventing the possible devastating effects of future hemorrhages.

A precise understanding of the location of the aneurysm in the Sylvian fissure, the depth of the fissure itself, the projection of the aneurysmal sac and its relationship to the efferent branches and to the lenticulo-striate arteries is a prerequisite for a safe exclusion of the aneurysm [4, 9, 16, 20, 21]; all this information can be obtained through a careful study of preoperative angiography (or angio-CT) and MRI. Also, the morphology of branching of the MCA entails considerable importance, as emphasized by several authors [16, 20]; for example, an arrow-shaped bifurcation is more difficult to handle surgically than the more common T-shaped or V-shaped bifurcations [12, 16].

During surgery, a strategy of exclusion that considers a remodeling of the sac and the use of double (or multiple) clips (especially for large aneurysms or aneurysms with a large neck) is the main clue to a successful and safe occlusion [4, 16, 20]; this can be done by temporary clipping and shrinking the sac with low-current bipolar coagulation, and with the use of fenestrated clips positioned perpendicular to the first clip and to the main axis of the neck, in order to exclude basal pouches (or "dog-ears") as well [3]. For large, partially thrombosed aneurysms, of the intra-aneurysmal thrombi can also be performed safely through temporary vessel occlusion.

As reported in another paper by our group, we have seen that intermittent temporary clipping can prolong the "stroke-free" period of occlusion even in a terminal artery such as the MCA [8]; in the present series, occlusion periods of over 10 min – required in specific cases and performed with intermittent modality – have been tolerated in the majority of cases. If long occlusion periods are anticipated, the use of intraoperative neurophysiological monitoring [5] could enhance safety in selected cases.

Intraoperative flowmetry, introduced by Charbel [2], constitutes a real advance in the treatment of middle cerebral aneurysms, since the possibility of clip-induced stenosis on the branching vessels is more frequent in this location, owing to the peculiar anatomical features of the MCA division. The Charbel probe allows a precise measurement – pre-and post-clip – of flow through the efferent MCA branches, and is more accurate than Doppler and even indocyanine green video-angiography in the evaluation of a hemodynamically significant stenosis; in our opinion, the introduction of this tool has definitely increased the safety of surgical exclusion for this aneurysmal location.

In conclusion, we believe that by developing a safer strategy for exclusion, surgical indications for unruptured MCA aneurysms should be expanded in the near future, thereby preventing the deleterious effects of the intraparenchymal hemorrhages that are so commonly observed after rupture of an aneurysm in this location.

Conflict of Interest Statement We declare that we have no conflict of interest.

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Progress in the Treatment of Unruptured Aneurysms

Hiroshi Tenjin, Seisuke Tanigawa, Michiko Takadou, Takahiro Ogawa, Ayako Mandai, Masataka Nannto, Yasuhiko Osaka, and Yoshikazu Nakahara

Abstract Recent technological progress has reduced the complication rate of unruptured aneurysm. We treated 128 unruptured aneurysms between April 2006 and March 2012. Seventy-six aneurysms (59 %) were clipped and 52 (41 %) were coil embolized. After 2010, we applied new instruments, i.e., near-infrared indocyanine-green videoangiography (ICG), an intraoperative endoscope, preoperative detailed MRI, and a stent-assisted coil embolization. In the results: (1) In 60 aneurysms treated before 2009, three patients showed a deterioration of more than two points in mRS (5 %). In 68 aneurysms treated after 2010, no patients showed deterioration (0 %) (p: n.s.). (2) No patients died and 126 patients (98 %) were discharged to home directly. (3) No patients showed rupture after treatment. In conclusion, the appropriate selection of treatment and recent technological progress have facilitated sophisticated treatment of unruptured aneurysms. Recently, the complication rate in surgery and endovascular surgery for unruptured aneurysms has become acceptably low.

Keywords Unruptured aneurysm • ICG • Endoscopy • Detailed MRI • Stent-assisted coil embolization

Introduction

Subarachnoid hemorrhage due to rupture of an aneurysm still leads to a high mortality rate despite its being a common disease. Because the rupture of a cerebral aneurysm cannot be predicted precisely, treatment of an unruptured aneurysm is preferable if the complication rate is very low. Recent technological progress has reduced the complication rate to an acceptable level. Here, some new technologies used in our department are introduced.

H. Tenjin (✉) • S. Tanigawa • M. Takadou • T. Ogawa • A. Mandai
M. Nannto • Y. Osaka • Y. Nakahara
Department of Neurosuregery, Kyoto Second Red Cross Hospital, Kamanza-Marutamachi, Kamigyoku, Kyoto 602-8026, Japan
e-mail: htenjin@nn.iij4u.or.jp

Methods

We treated 128 unruptured aneurysms between April 2006 and March 2012. The patients' ages ranged from 28 to 80 years old (63.9 ± 7.9). Seventy-six aneurysms (59 %) were clipped and 52 (41 %) were coil embolized (Tables 1 and 2). Sixteen aneurysms were larger than 10 mm in diameter. After 2010, we applied new instruments, i.e., near-infrared indocyanine-green videoangiography (ICG), an intraoperative endoscope, preoperative detailed MRI, and stent-assisted coil embolization.

In 14 clippings, we confirmed the patency of parent arteries or perforators using ICG. In two complicated clippings, endoscope-assisted procedures were performed (Olympus Optical Corp., Tokyo, Japan).

We prospectively studied the details of MR images in 30 patients with 31 aneurysms. MR examinations were performed using a Magnetom Avanto 1.5T (Siemens, Erlangen, Germany). The aneurysm wall was evaluated by black-blood magnetic resonance angiography (BBMRA). BBMRA was obtained as a three-dimensional T1-weighted image with 1mm slice thickness, TR 400 ms, TE 13 ms, flip angle of 120, and pixel size of 0.9 × 0.7 × 1.0 mm. The relationship of the aneurysm with the brain and brain nerves, especially tight contact with surrounding tissue, was depicted by MRI using steady-state free precession (SSFP). SSFP was obtained with a gradient field echo, 0.5 mm slice thickness, TR 6.17 ms, TE 2.72 ms, flip angle of 70, acquisition time of 4 min, and pixel size of 0.8 × 0.6 × 0.5 mm.

Cordis Enterprise stent, a nitinol, self-expanding microstent with a closed-cell design (Cordis Neurovascular, Miami, U.S.A.), was used for coil embolization in three large wide-neck aneurysms.

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Table 1 Distribution of unruptured aneurysm sites and treatment

	Clipping	Coil embolization	Total
IC cavernous	0	5	5
IC paraclinoid	4	17	21
ICPC	14	6	20
IC ant. chor.	1	1	2
IC top	2	4	6
MC	35	1	36
AcomA	18	7	25
AC dist.	2	3	5
VA-PICA	0	3	3
BA top	0	5	5
	76	52	128

IC cavernous internal carotid artery cavernous portion, *IC paraclinoid* internal carotid artery paraclinoid portion, *ICPC* internal carotid artery posterior communicationg artery bifurcation, *IC ant. chor* internal carotid artery anterior choroidal artery bifurcation, *IC top* internal carotid artery terminal portion, *MC* middle cerebral artery, *AcomA* anterior communicating artery, *AC dist*. anterior cerebral artery distal portion, *VA-PICA* vertebral artery posterior inferior cerebellar artery bifurcation, *BA top* basilar artery terminal portion

Table 2 Distribution of unruptured aneurysm sizes and treatment

	Clipping	Coil embolization	Total
Less than 3 mm	0	0	0
3–3.9 mm	4	4	8
4–4.9 mm	10	7	17
5–5.9 mm	24	7	31
6–6.9 mm	15	16	31
7–7.9 mm	6	7	13
8–8.9 mm	6	3	9
9–9.9 mm	2	1	3
More than 10 mm	9	7	16
	76	52	128

Results

1. Modified Rankin Scale: Three patients showed a deterioration of more than two points in mRS (2.3 %). In 60 aneurysms treated before 2009, three patients showed a deterioration of more than two points in mRS (5 %). In 68 aneurysms treated after 2010, no patients showed deterioration (0 %) (p: n.s.).
2. No patients died and 126 patients (98 %) were discharged to home directly.
3. No patients showed rupture after treatment.

Representive Cases

Case 1

A 68-year-old male. An anterior communicating artery aneurysm of 6 mm was found on brain screening (Fig. 1a). SSFP and BBMRA showed a sufficient working space around the aneurysm (Fig. 1b, c). Dissection of the aneurysm was not difficult (Fig. 1d). The post-operative course was uneventful.

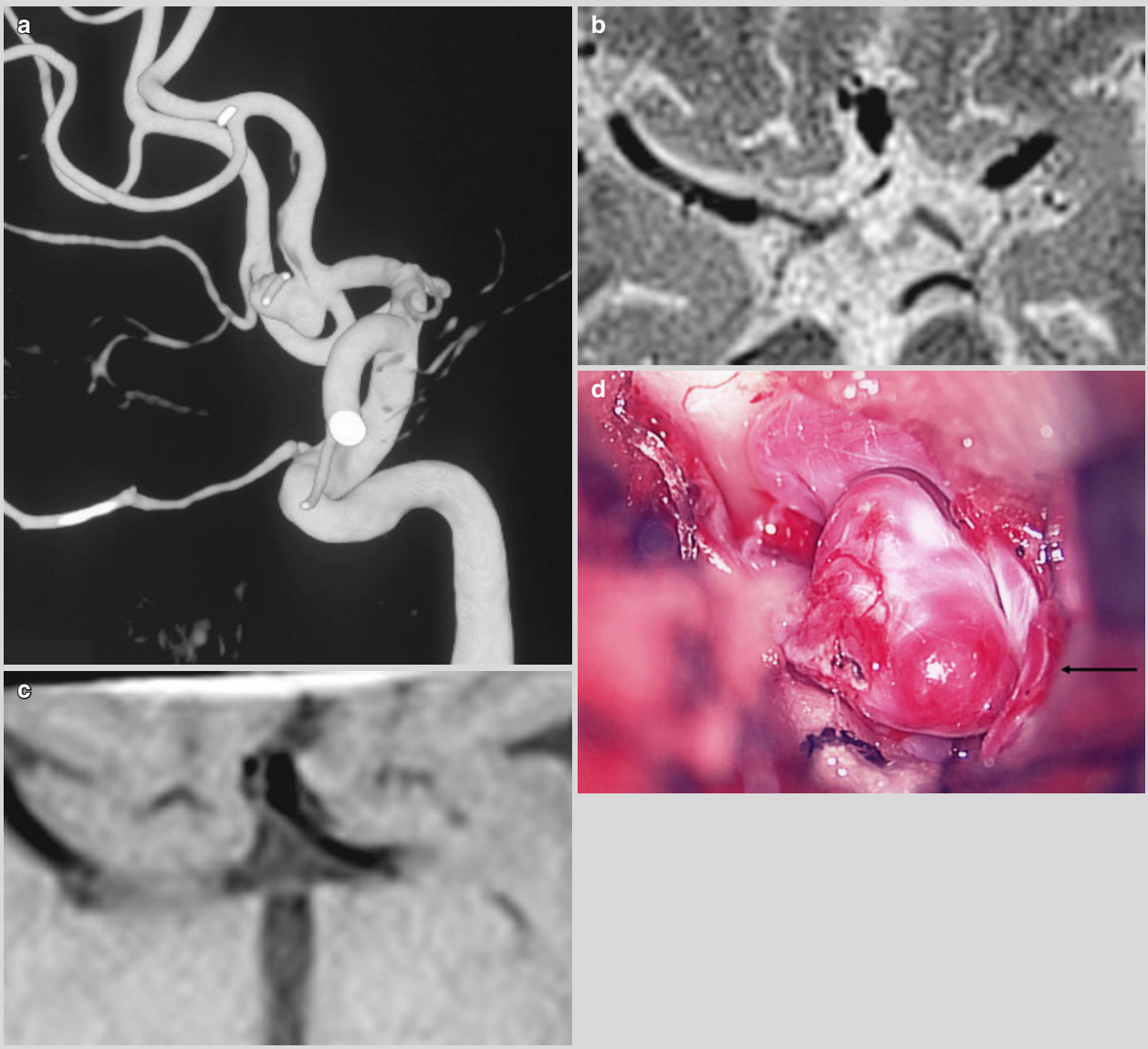

Fig. 1 (**a**) Left carotid angiography of case 1. (**b**) SSFP. (**c**) BBMRA. (**d**) Surgical view. *Arrow* indicates no adhesion between the aneurysm and brain

Case 2

A 26-year-old female. A germ cell tumor had been removed 4 years previously. A de-novo aneurysm of around 3 mm had developed in the anterior communicating artery (Fig. 2a, b). A pterional approach was used. Because the aneurysm had adhered to the surrounding tissue, it was simultaneously dissected using an endoscope (Fig. 2c). The post-operative course was uneventful.

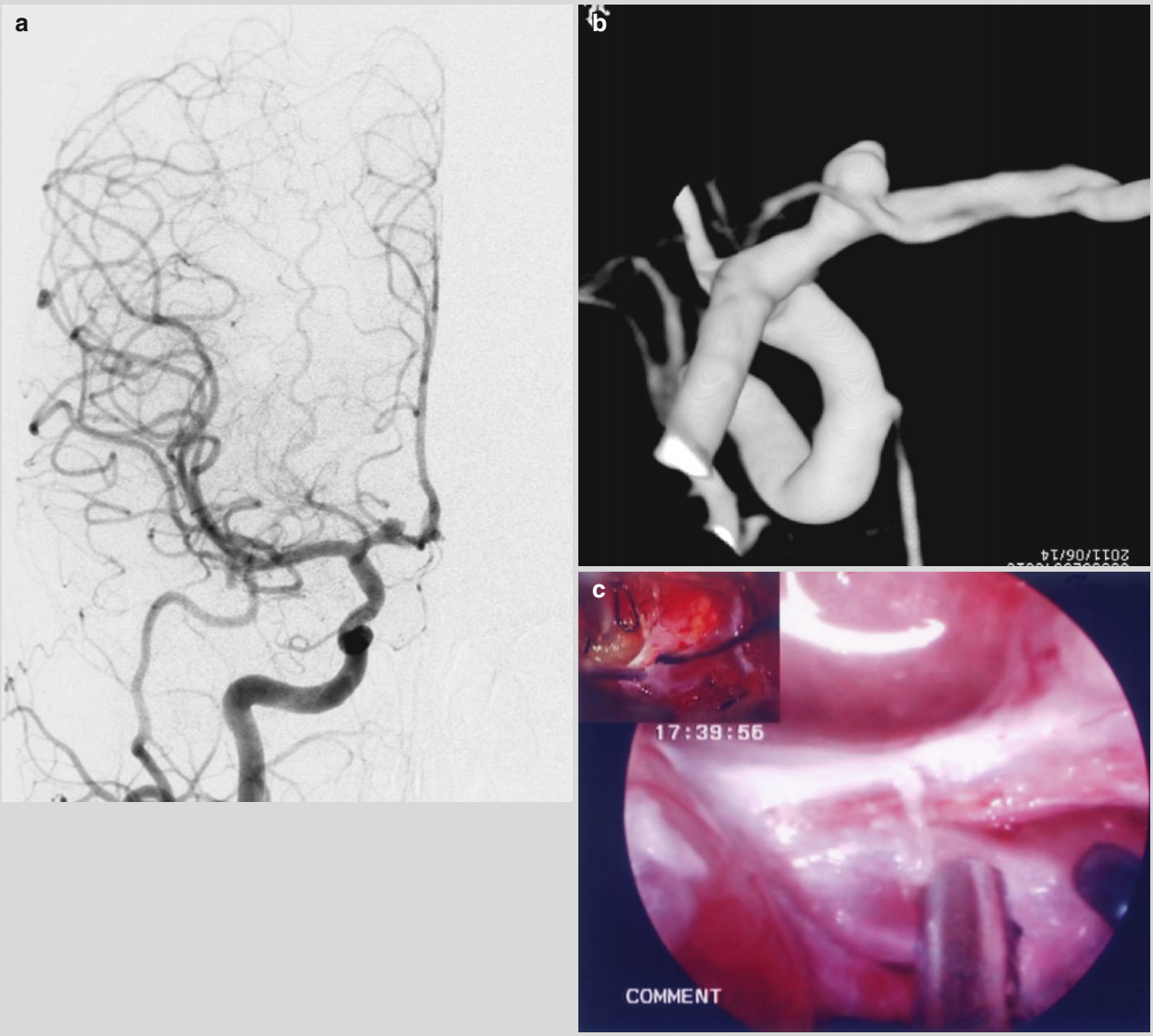

Fig. 2 (**a**) Right carotid angiography of case 2 (A-P view). (**b**) 3D angiography. (**c**) Surgical view, microscopic view shown in endoscopic view

Case 3

A 64-year-old female. A large right vertebral artery aneurysm was detected on brain screening. The aneurysm was embolized using a self-expanding stent (Fig. 3a). The post-operative course was uneventful (Fig. 3b).

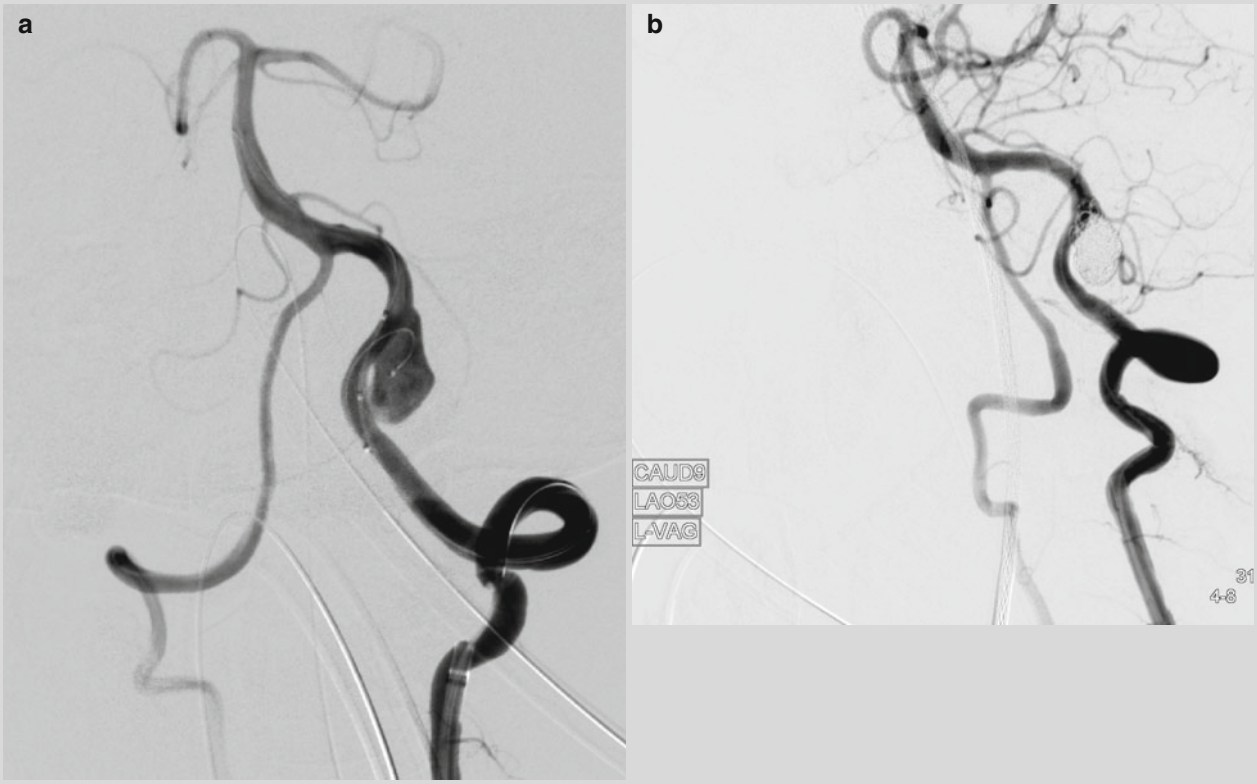

Fig. 3 (**a**) Left vertebral angiography of case 3. (**b**) Left vertebral angiography after stent-assisted coil embolization

Discussion

The unruptured aneurysm rupture rate is not precisely known. ISUIA is a well-known study, although the low rupture rate was criticized [3]. In the Japanese population, the total rupture rate of unruptured aneurysms was reportedly 0.95 % per year including small aneurysms of more than 3 mm [10]. Therefore, if the rate of surgical complication is acceptably low, preventive aneurysm clipping of more than 3 mm in diameter is reasonable.

Recent technological progress has reduced the complications of unruptured aneurysm treatment. By-flow visualization during surgery using ICG, accidental parent artery or perforator occlusion can be avoided [6]. The microscopic surgical view is restricted. If an aneurysm exists behind the parent artery, i.e., internal-carotid artery posterior communicating artery aneurysm which protrudes medially, clipping is sometimes difficult with only a microscopic view. An endoscopic view is helpful to observe behind the parent artery [2, 5]. BBMRA is simple and useful for evaluating the aneurysm wall. A thick or thin aneurysm wall on BBMRA enables the surgeon to predict the surgical findings. The SSFP image is useful for visualizing the cisternal segments of cranial nerves, because this sequence provides excellent contrast resolution between the CSF and nerves [8, 9]. The capability of distinguishing between the aneurysm, small arteries, and surrounding environment has been reported [4, 7]. Here, we used an SSFP image to detect tight aneurysmal contact with surrounding tissues with visible CSF.

Stent-assisted coil embolization is a useful new technology [1]. Broad neck aneurysms that are hard to clip can be treated with a low complication rate.

Conclusion

The appropriate selection of treatment and recent technological progress have facilitated sophisticated treatment for unruptured aneurysms. Recently, the complication rate in surgery and endovascular surgery for unruptured aneurysms has become acceptably low.

Conflict of Interest We declare that we have no conflict of interest.

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Distal Basilar Artery Aneurysms: Conditions for Safe and Secure Clipping

Tadayoshi Nakagomi

Abstract In general, vertebro-basilar aneurysms are good indications for endovascular treatment. However, basilar artery (BA) bifurcation aneurysms, BA-superior cerebellar artery (SCA) aneurysms, and sometimes mid-basilar aneurysms are also good indications for clipping. In this paper, conditions for safe and secure clipping for distal basilar aneurysms are discussed.

There are several tips for the clipping of distal BA aneurysms. Among them, the following are very important: patency of the perforators, posterior cerebral artery (P1), and SCA must always be maintained. Several modalities including micro-Doppler ultrasonography and indocyanine green video-angiography (ICGVA) should be used to confirm the patency of these vessels. Each confirmation of patency of the vessels after clipping must be compared to those from before the clipping. Intra-operative digital subtraction angiography (DSA) is needed for large or giant aneurysms.

Keywords Intracranial aneurysm • Surgical clipping • Basilar artery aneurysm • TIPS

In general, vertebro-basilar aneurysms are good indications for endovascular treatment [2, 5, 6]. However, basilar bifurcation (BA-bif) aneurysms, BA-superior cerebellar artery (BA-SCA) aneurysms, and sometimes mid-basilar aneurysms are also good indications for this procedure [4, 9]. On the other hand, surgical clipping is relatively contraindicated for elderly patients, in particular those in poor clinical condition, as well as for large or giant aneurysms.

There are several important things to keep in mind in operative planning for BA-bif and BA-SCA aneurysms; these include projection of the dome, height of bifurcation, or distance from the neck of the aneurysm to posterior clinoid process, size of the neck, location of the perforators, origin of the neck, size of posterior communicating (Pcomm) artery, etc. The aneurysms where the neck is 5–10 mm above the clinoid line are suitable for a pterional approach [3] (Fig.1, upper left).

BA-bif and BA-SCA aneurysms can be approached using pterional craniotomy. A basilar top complex that looks like a dragonfly appears when Liliequist's membrane is opened, and the optimal route to the aneurysm's neck, lateral to internal carotid artery (ICA), medial to ICA, or posterior to ICA, is selected (Fig. 1, upper right).

There are several tips for clipping distal BA aneurysms [1]. Superficial Sylvian and frontobasal veins must be preserved. Proximal control at the proximal BA should be prepared, in particular, when the height of the neck is low or the size of the aneurysm is large. It is very useful to soften the dome during neck dissection and clip placement. For emergent control for intra-operative rupture, proximal control of BA is absolutely necessary. For this purpose, posterior clinoidectomy is sometimes carried out. The drilling during the posterior clinoid process must be done meticulously. Retraction or division of the anterior tentorium is sometimes effective for proximal control of BA. Perfect clipping must be carried out after the BA-complex is confirmed. After surgical clipping, it is important to verify that the aneurysm is excluded, perforators are patent, and P1 and SCA are patent.

Several representative cases are shown here.

Case 1 is a 60-year-old female who suffered from a subarachnoid hemorrhage (SAH). Her clinical grade was IV according to WFNS grading. Surgical clipping for BA-bif An was carried out 10 days after the onset of SAH (Fig. 1, lower left).

Case 2 is a 65-year-old female who suffered from SAH. First, endovasucular coiling was carried out. Follow-up angiograms revealed a neck remnant, so clipping for BA-bif aneurysm was performed (Fig. 1, lower right).

Case 3 is a 65-year-old female who suffered from SAH; a ruptured distal anterior cerebral artery aneurysm was

T. Nakagomi, MD
Department of Neurosurgery,
Teikyo University School of Medicine,
2-11-1 Kaga, Itabashi City, Tokyo, 173-8605, Japan
e-mail: nsnaka@med.teikyo-u.ac.jp

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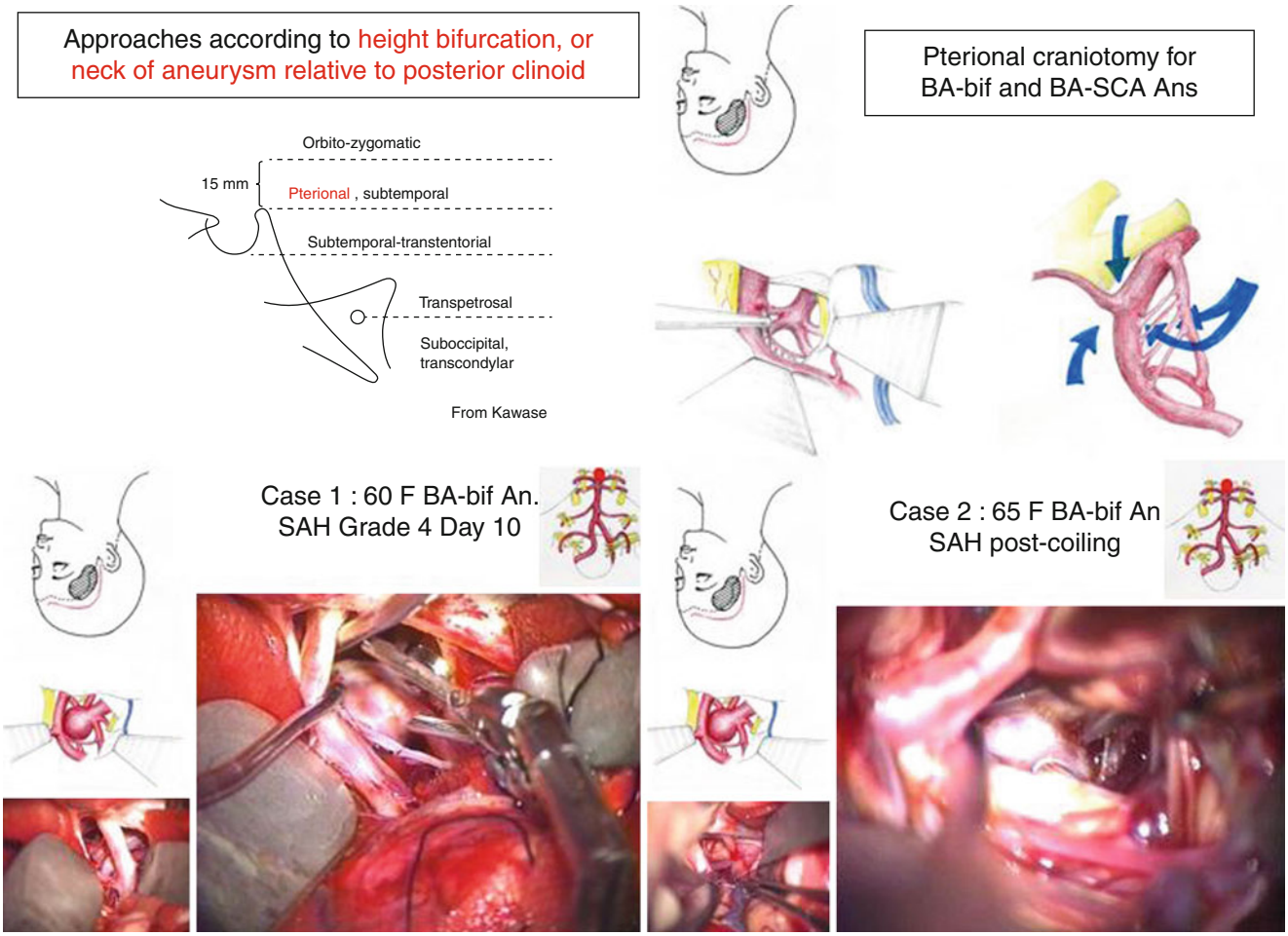

Fig. 1 *Upper left*: Surgical approaches according to height of bifurcation or neck of basilar distal aneurysm relative to posterior clinoid. *Upper right*: Surgical routes for the distal basilar aneurysms when pterional craniotomy is selected. *Lower left*: Intra-operative photographs of Case 1. *Lower right*: Intra-operative photographs of Case 2

successfully clipped. Surgical clipping for an unruptured BA-bif aneurysm was carried out (Fig. 2, upper left).

Case 4 is a 47-year-old male who suffered from SAH. His clinical grade was II according to WFNS grading. Surgical clipping for a BA-trunk aneurysm was carried out 1 day after the onset of SAH (Fig.2, upper right). In this case, posterior clinoidectomy was carried out.

Case 5 is a 50-year-old female. Surgical clipping was done for her unruptured L.BA-SCA aneurysm (Fig. 2, lower left)

Case 6 is a 45-year-old female who suffered from SAH. Her ruptured middle cerebral artery aneurysm was successfully clipped. Surgical clipping for unruptured BA-SCA aneurysm was performed (Fig. 2, lower right).

Case 7 is a 59-year-old female who suffered from SAH and had been admitted to another hospital. CTA and DSA revealed a partially thrombosed BA-SCA aneurysm (Fig. 3, upper left). Coil embolization was performed immediately. A follow-up DSA showed refilling of the neck, so a second coil embolization was performed.

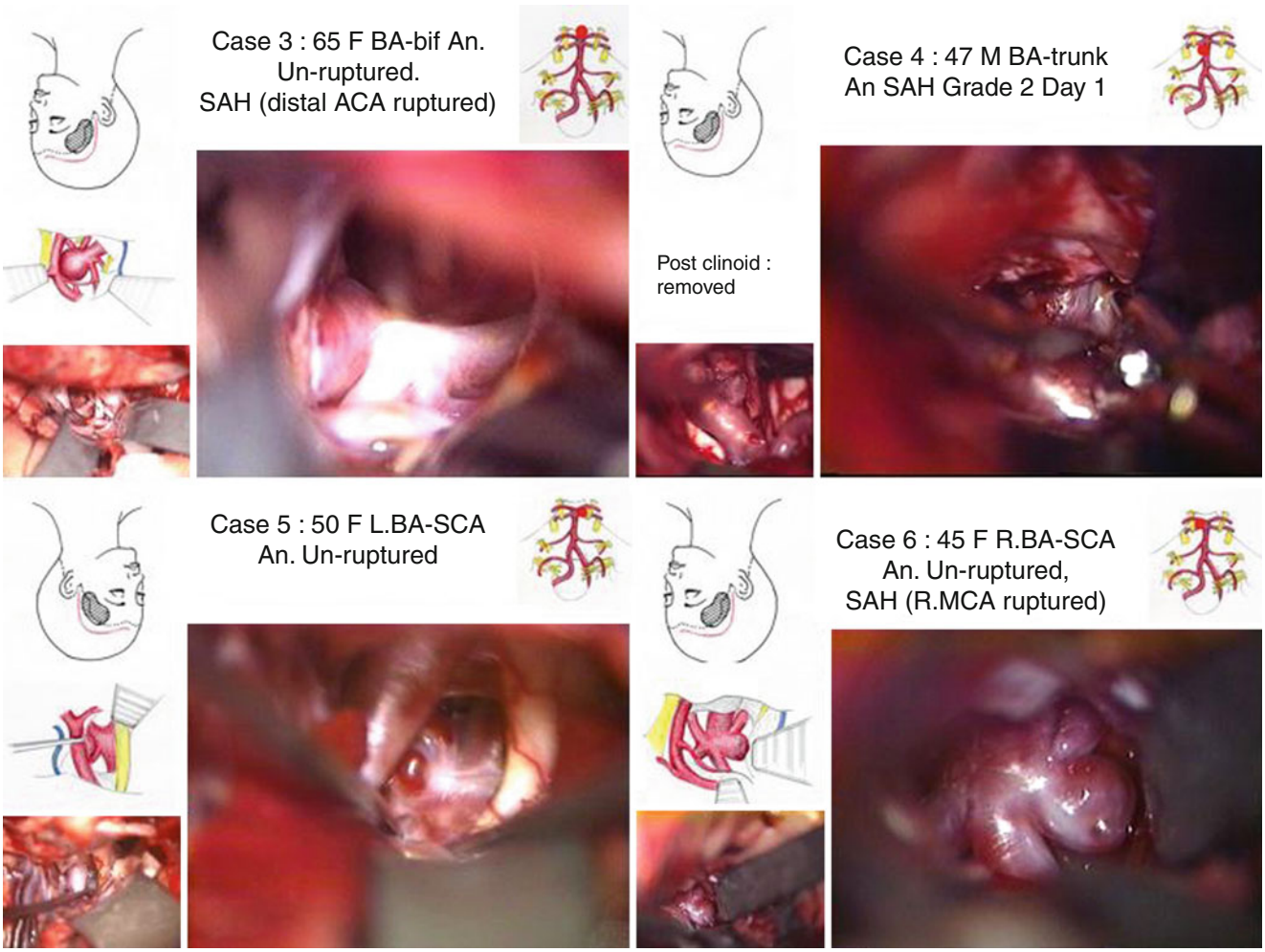

Fig. 2 *Upper left*: Intra-operative photographs of Case 3. *Upper right*: Intra-operative photographs of Case 4. *Lower left*: Intra-operative photographs of Case 5. *Lower right*: Intra-operative photographs of Case 6

However, the neck of the aneurysm was not completely obliterated (Fig. 3, upper right). The patient was referred to our hospital. We decided that her BA-SCA aneurysm was a relatively good indication for surgical clipping. A DSA taken the day before the craniotomy shows refilling of the neck. The neck of the aneurysm seemed to have enough space for clipping (Fig. 3, upper right) so we decided not to remove coils in the arterial lumen.

A modified right orbito-zygomatic temporo-polar approach [7, 8] with both anterior and posterior clinoid removal was chosen. Surgical clipping seemed to be carried out without any problems (Fig. 3, lower left). The patency of SCA was confirmed by micro-Doppler ultrasonography. An intra-operative ICG-VA was done after placing the clip and it revealed a patent SCA. The next day, however, a high intensity area was noted in the cerebellum on DWI (Fig. 3, lower right). Two possible reasons for this were given: clipping of the aneurysm resulting in stenosis of the SCA, or a placed clip moved toward a BA. To avoid these complications, confirmation of the patency of SCA by intra-operative DSA or placing the final clip after coil removal are recommended.

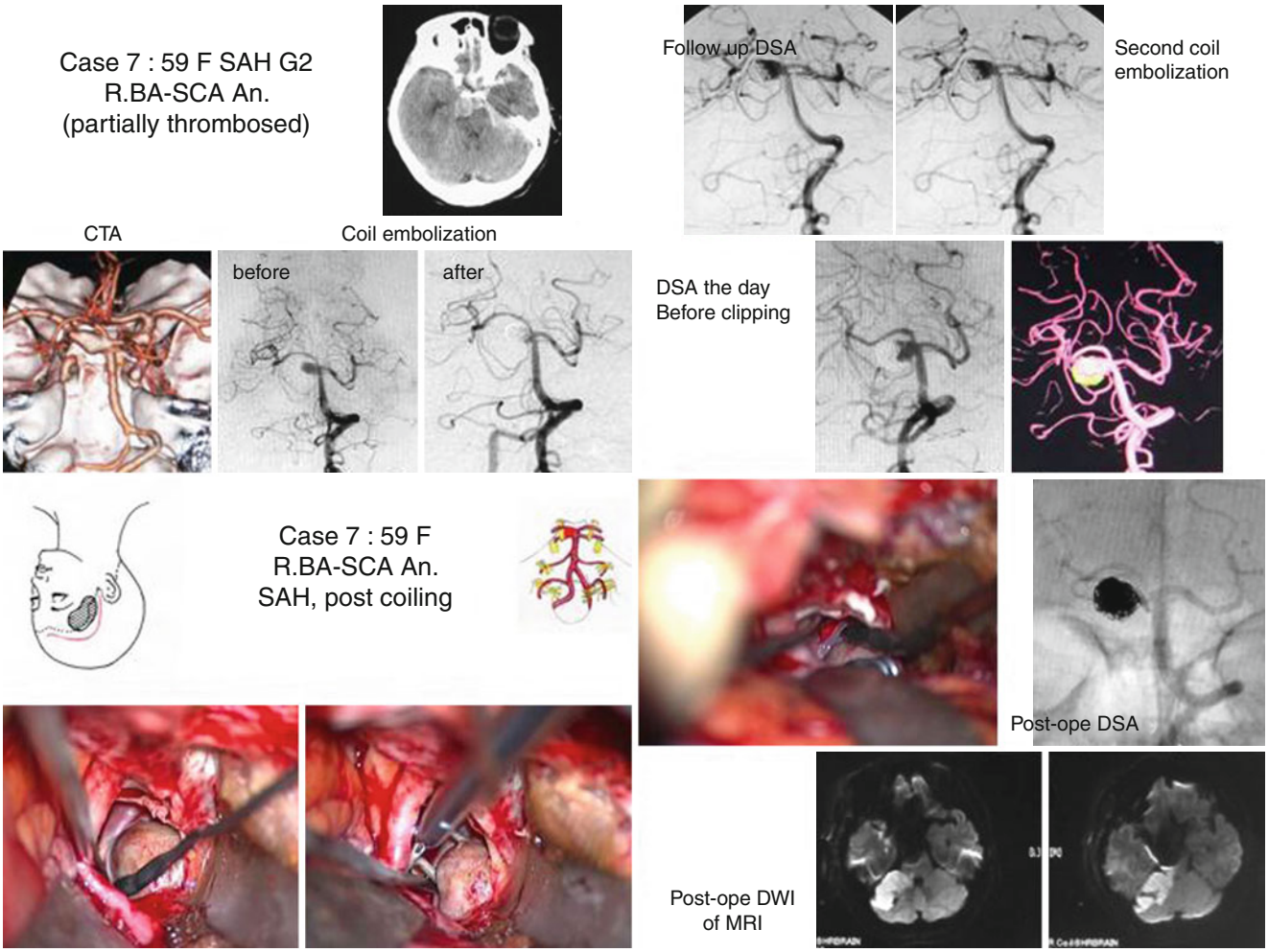

Fig. 3 *Upper left*: CT and DSA of Case 7. *Upper right*: Follow up DSA of Case 7. *Lower left*: Intra-operative photographs of Case 7. *Lower right*: Intra-operative photograph and Postoperative MRI and DSA of Case 7

Conclusion

There are several TIPS for the clipping of distal BA aneurysms. Among them, the following are very important for safe and secure clipping: First of all, patency of the perforators, P1, and SCA must always be maintained. Several modalities including micro-Doppler ultrasonography and ICG-VA should be used to confirm patency of these vessels. Each confirmation of patency of the vessels after clipping must be compared to those before clipping. Intra-operative DSA is necessary for large or giant aneurysms.

Conflict of Interest We declare that we have no conflict of interest.

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Role of Bypass Surgery and Balloon Occlusion Test for the Endovascular Management of Fusiform Dissecting Aneurysms. Report of Two Cases

Michihiro Tanaka, Hidetsugu Maekawa, Yoshinori Sakata, Yujiro Obikane, Hiromu Hadeishi, and Ayako Yamazaki

Abstract Fusiform intracranial aneurysm is one of the most difficult pathologies to treat. The role and efficacy of recent advanced endovascular technique and conventional bypass surgery are discussed.

Keywords Fusiform aneurysm • EC-IC bypass • Leptomeningeal anastomosis • Endovascular management • Balloon occlusion test

Abbreviations

3D-RA	Three dimensional rotation angiography
CT	Computed tomography
DSA	Digital subtraction
MCA	Middle cerebral artery
PCA	Posterior cerebral artery
PICA	Posterior inferior cerebellar artery
SAH	Subarachnoid hemorrhage EC-IC extracranial-intracranial
SCA	Superior cerebellar artery
STA	Superficial temporal artery

Introduction

Clinical features of nontraumatic intracranial dissecting aneurysms remain unclear, and management of fusiform aneurysms is a significant challenge for neurosurgeons because neither microsurgical nor endovascular techniques are effective for the treatment of this type of aneurysm. Recently developed innovative devices and endovascular technology allow the deployment of stents alone or with coiling in certain groups of fusiform aneurysms [1, 6–8, 12, 14]; however, there are still many technical limitations [1, 4, 8, 10]. Self-expandable stents (e.g., Enterprise) available today are still too stiff and large to deliver to the peripheral arteries. This stiffness may cause further dissection at the level of the aneurysmal wall and might be associated with a potential risk of rupture. In addition, the application of stents requires dual antiplatelet therapy prior to the intervention. This medication may also increase the risk of premature rupture in the acute phase of subarachnoid hemorrhage (SAH). Therefore, the most reliable and secure strategy in the management of fusiform aneurysm is the trapping of the pathological segment with parent artery occlusion, if the patient has tolerance with sufficient collateral circulation; otherwise, appropriate revascularization can be performed [3, 5, 11]. The endovascular techniques of internal trapping with platinum coils and extracranial to intracranial (EC-IC) bypass surgery have been well established during the past few decades. Indication for EC-IC bypass should be defined based on a tolerance test with a balloon occlusion test under the precise localization of a microballoon catheter. Here we discuss the role and efficacy of a selective balloon occlusion test and endovascular internal trapping procedure combined with EC-IC bypass.

Case Reports

Case 1

A 53-year-old male presented with sudden loss of consciousness and slight left hemiparesis. Emergency computed tomography (CT) showed subarachnoid hemorrhage predominantly distributed in the left interpeduncular cistern and prepontine cistern (Fig. 1).

His initial clinical condition was Hunt and Hess grade IV. Three-dimensional CT and diagnostic angiography showed an upper basilar trunk fusiform-shaped aneurysm located dis-

M. Tanaka, MD, PhD (✉) • H. Maekawa, MD
Y. Sakata, MD • Y. Obikane, MD • H. Hadeishi, MD, PhD
A. Yamazaki, MD, PhD
Department of Neurosurgery, Kameda Medical Center, Higashi-cho 929, Kamogawa City, Chiba 296-8602, Japan
e-mail: michihiro@attglobal.net

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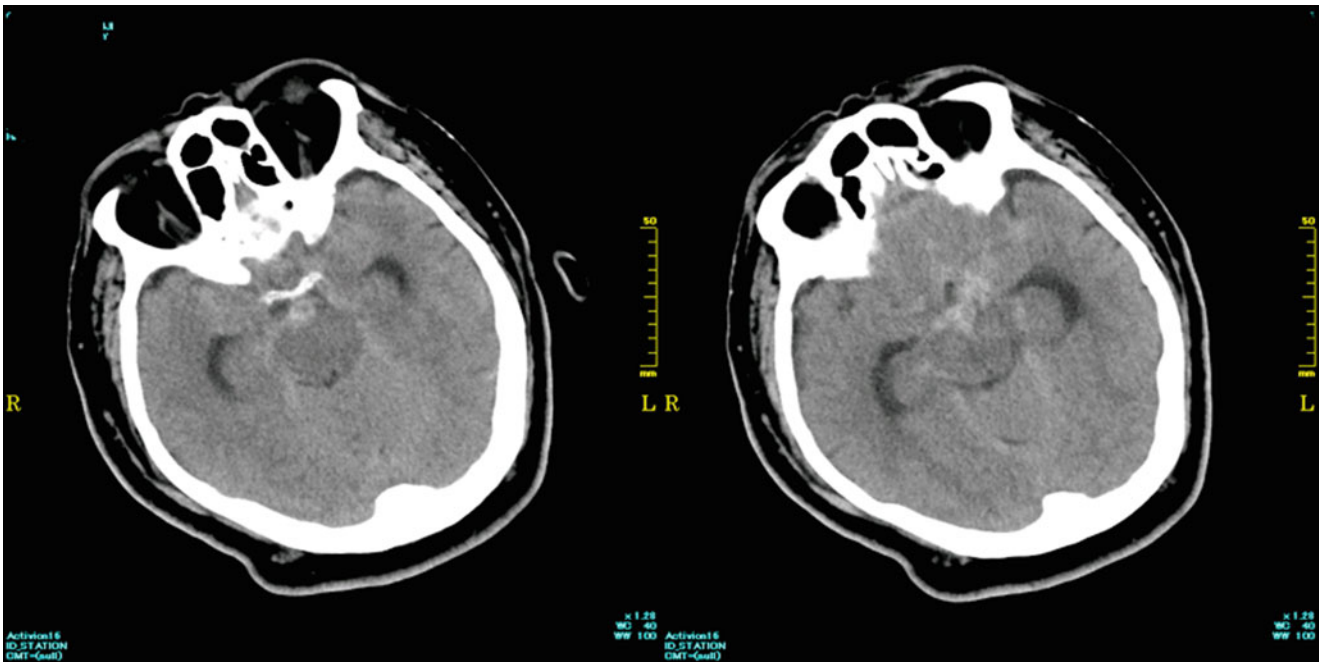

Fig. 1 An emergency CT on admission showed SAH mainly distributing in the interpeduncular and prepontine cistern

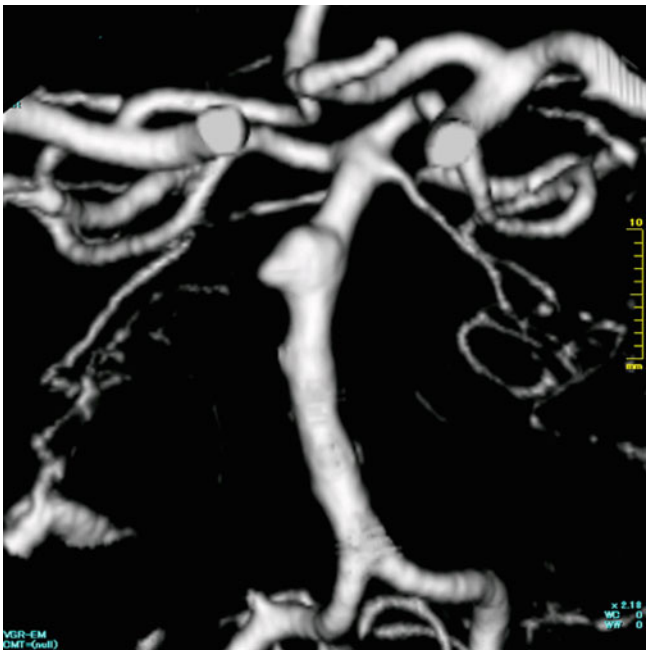

Fig. 2 A 3D-CT showed a dysmorphic fusiform aneurysm located in the upper basilar trunk

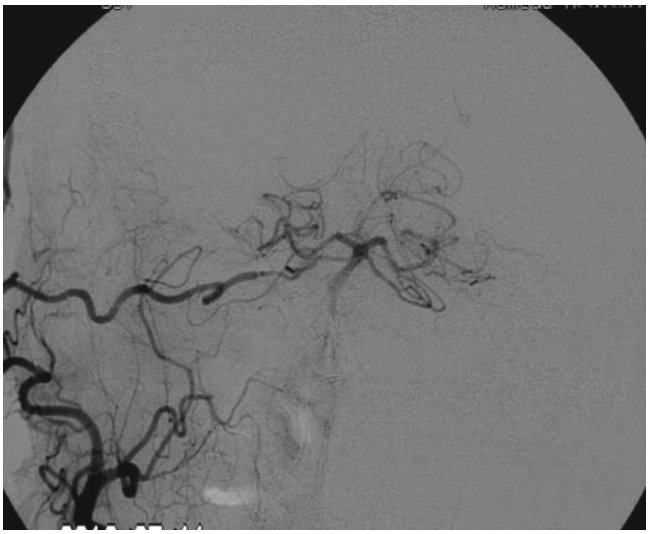

Fig. 3 Right external carotid angiography under the balloon occlusion of basilar trunk is showing bilateral PCA supplied from the STA-SCA bypass

tal to the anterior inferior cerebellar artery (Fig. 2). Original source images of multidetector computerized tomography (Multi-detector-CT) and magnetic resonance imaging (MRI) (T_2-weighted images) showed a dysmorphic wall of the aneurysm with the double lumen sign. Since the preservation of the basilar trunk was not feasible because of its anatomical configuration, EC-IC bypass [superficial temporal artery (STA)–superior cerebellar artery (SCA)] and endovascular trapping were performed 14 days after the onset of SAH.

Bypass operation: Under general anesthesia, a 10-cm segment of parietal branch of the superficial temporal artery (STA) was anastomosed to a hemispheric branch of the superior cerebellar artery (SCA) through a right subtemporal approach (Figs. 3 and 4).

Endovascular procedure: Immediately after this STA-SCA bypass surgery, the patient was moved to an angiography suite. A selective balloon occlusion test was performed

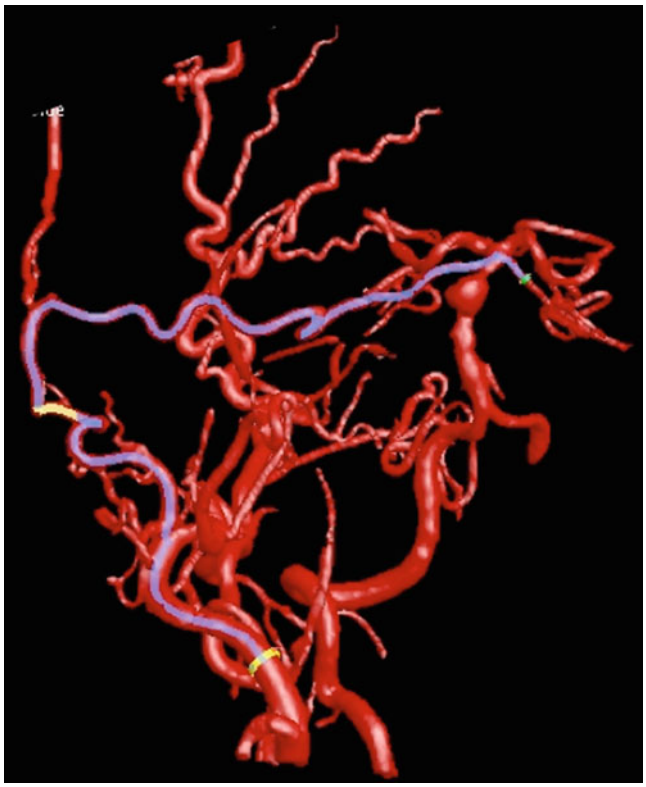

Fig. 4 A 3D rotation angiography delineates the distribution of revascularization through the STA-SCA bypass

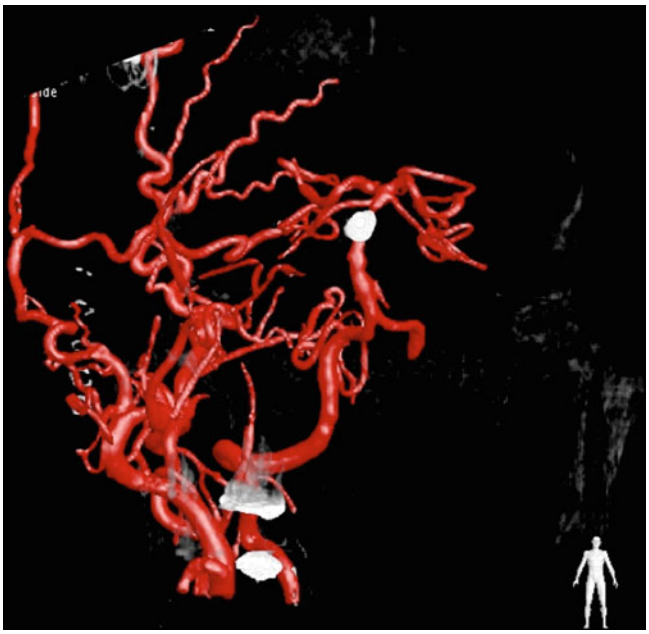

Fig. 5 Complete obliteration of fusiform aneurysm is seen, while bilateral distal PCA territory is supplied through the STA-SCA bypass

at the mid-basilar artery just proximal to this aneurysm with a microballoon catheter. Under this balloon occlusion, right external carotid angiography showed sufficient revascularization through this bypass and enough flow to the bilateral posterior cerebral artery, and SCA cortical territory was confirmed angiographically. Subsequently, embolization of aneurysmal lumen, including parent artery (internal trapping), was achieved (Fig. 5).

Postoperative course: He gradually regained consciousness and became alert and well oriented at 4 days post-surgery. However, his left hemiparesis remained. A postoperative MRI showed an infarction of the right paramedian nuclei of pons that was associated with the pontine perforators originating from the dissecting lesion. He went to the regional hospital for further physiotherapy with modified Rankin scale 3 at 60 days from the onset.

Case 2

A 54-year-old female presented with sudden onset of headache. An emergency CT showed an abnormally high density area of a round shape that was measured around 10 mm in diameter, localizing at the left quadrigeminal cistern and pulvinar thalamus. Initially this was diagnosed as a thalamic hemorrhage; however, an MRI and three-dimensional computerized tomography (3D-CT) images revealed a fusiform aneurysm locating left distal posterior cerebral artery (P3-P4 segment). Since the subarachnoid hemorrhage was negative on FLAIR images of the MRI, this was diagnosed as an impending ruptured aneurysm. Cerebral angiography showed a dysmorphic fusiform aneurysm at the left P3-P4 segment (Fig. 6a). Because the localization of this aneurysm was close to the tentorial notch, this was considered to be a dissecting aneurysm.

Endovascular procedure: Under general anesthesia in the angiography suite, a microballoon was navigated into the P2 segment that was just proximal to this aneurysmal lumen (Fig. 6b). Under inflation of this microballoon, the ipsilateral internal carotid angiography showed a sufficient collateral supply with retrograde filling of the parieto-occipital branch of the posterior cerebral artery (PCA) (Fig. 6c). Because of this, enough retrograde flow distributing to the distal lumen of the aneurysm, bypass surgery was not indicated in this case.

A 3D-rotational angiography (3D-RA) confirmed that this leptomeningeal anastomosis was mainly supplied from the angular artery of the middle cerebral artery (MCA) cortical territory (Fig. 7).

The aneurysm and its parent artery were obliterated with platinum coils, and a control ipsilateral internal carotid angiography revealed the complete obliteration of this aneurysm and sufficient collateral flow of PCA cortical territory distal to this aneurysm (Fig. 8).

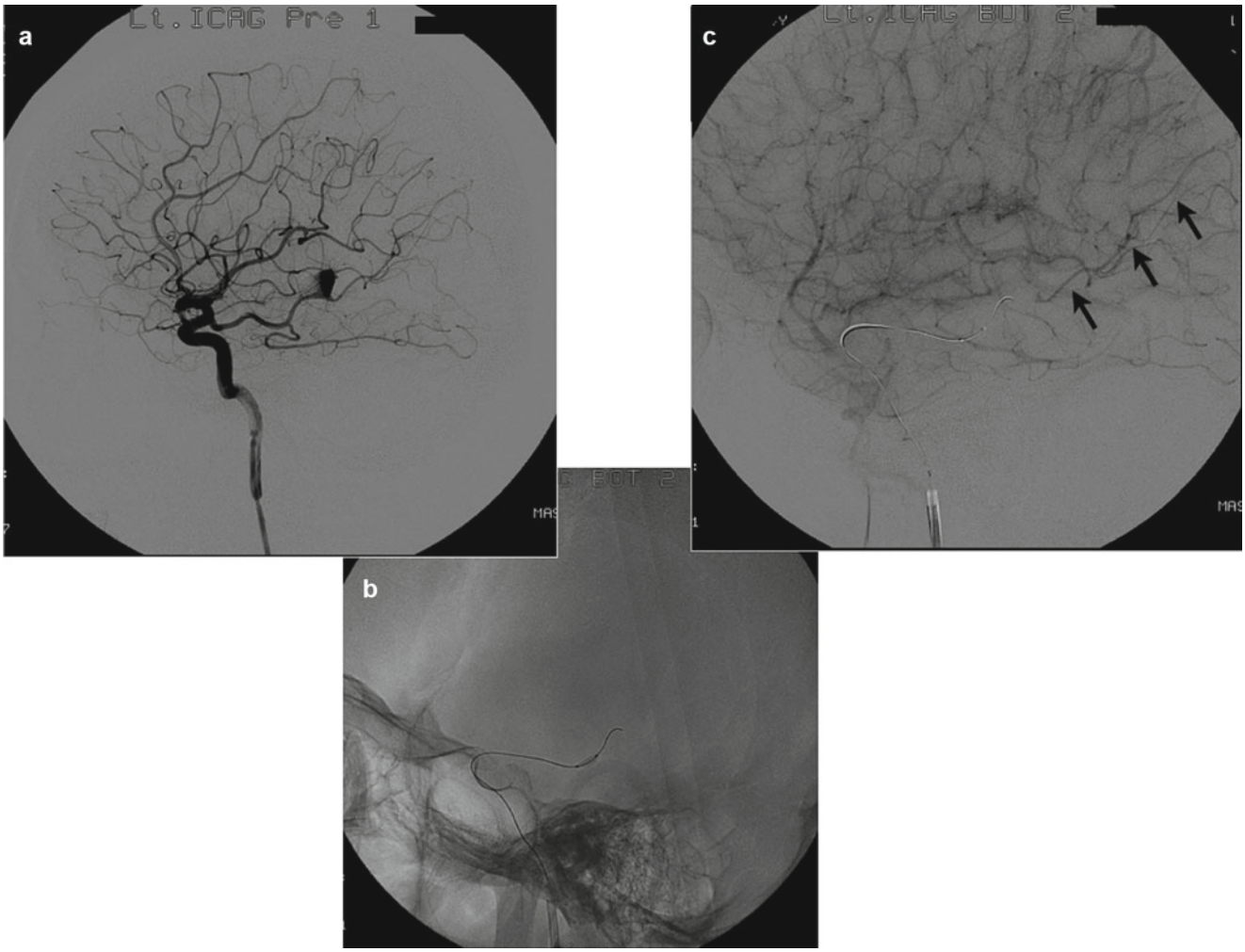

Fig. 6 (**a**) Left internal carotid angiography shows fusiform aneurysm locating distal PCA (P3-P4 segment). (**b**) Through the fetal type of posterior communicating artery, a microballoon catheter was navigated and inflated at the P3 segment that is just proximal to the aneurysm. (**c**) Left internal carotid angiography under balloon occlusion revealed a retrograde filling of P4 segment through the parieto-occipital branch of PCA. This functional test indicated sufficient collateral circulation through the leptomeningeal anastomosis from MCA cortical territory. It enables the trapping of the pathological lesion without hemodynamic compromise in the territory of PCA

Postoperative course: The patient recovered well without neurological deficit. A follow-up MRI showed complete obliteration of the dissecting aneurysm without ischemic lesion in the territory of PCA.

Discussion

Intracranial fusiform aneurysm is one of the most difficult lesions to treat, both endovascularly and surgically, because pathologically the damage or lack of the internal elastic lamina is often associated with aneurysm formation [9]. Recently, intracranial stents have been developed and widely used, especially for unruptured broad neck aneurysms. However, the application of these stents requires dual antiplatelet therapy and the incidence of perioperative complications related to these stent devices (e.g., ischemic compromise and mechanical distortion of perforators) is still higher than the conventional endovascular procedure without stent devices [6, 7, 12]. Therefore, if the appropriate revascularization were performed, or the patient had good tolerance of the parent artery occlusion, the obliteration of the aneurysm, including parent artery (endovascular trapping), is an ideal option for the exclusion of this pathology disease from the circulation in terms of long-term durability of the lesion as well as the prevention of rupture [5]. As a revascularization technique, EC-IC bypass has been used over the last 30 years. There are some limitations and technical difficulties of bypass surgery, especially in the posterior

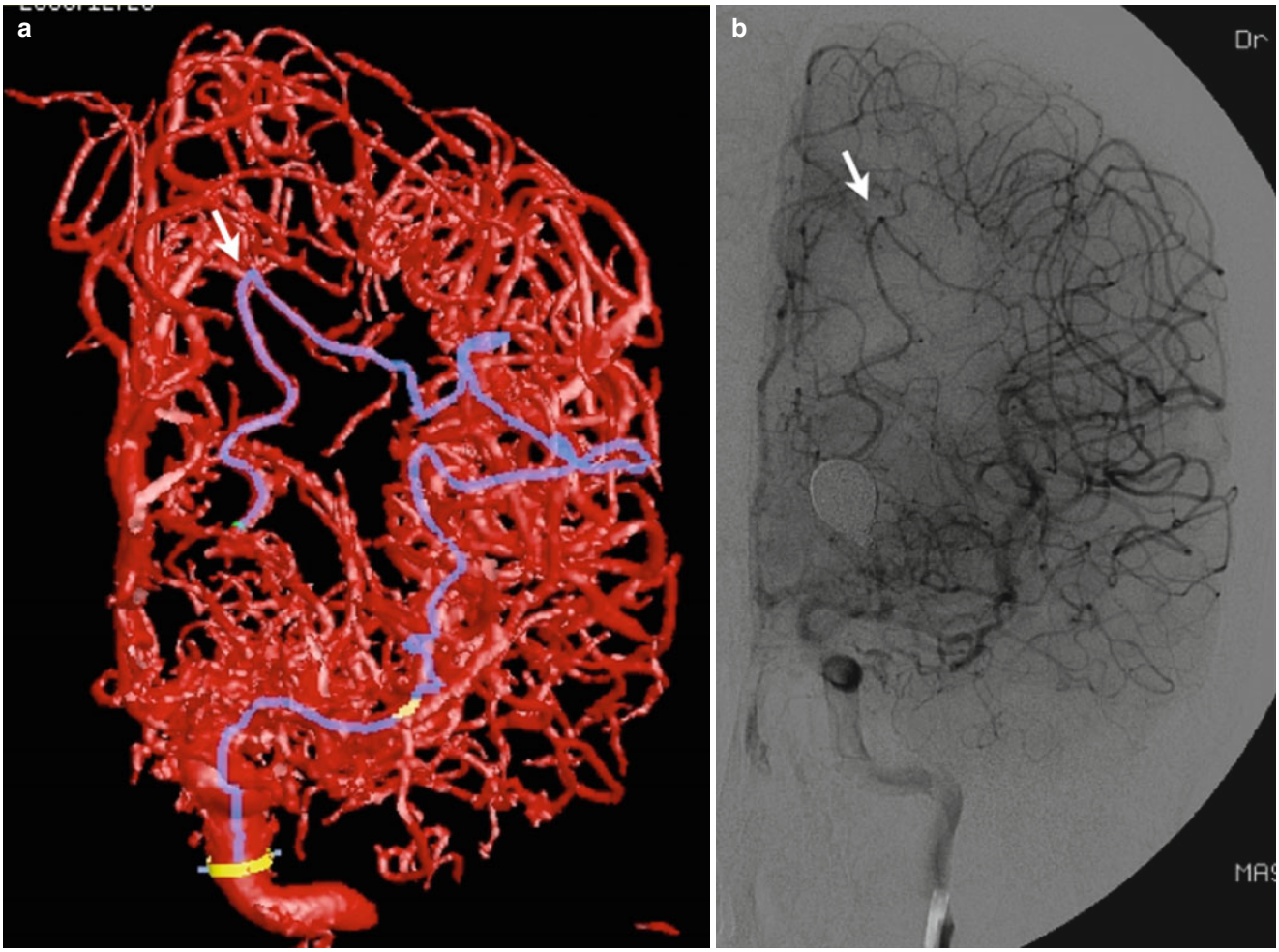

Fig. 7 (**a**, **b**) 3D-RA frontal view corresponding to the DSA showing retrograde filling to the parieto-occipital artery (*arrow*). Note the blue color line on 3D-RA. It delineates the collateral pathway of leptomeningeal anastomosis through the angular artery of MCA

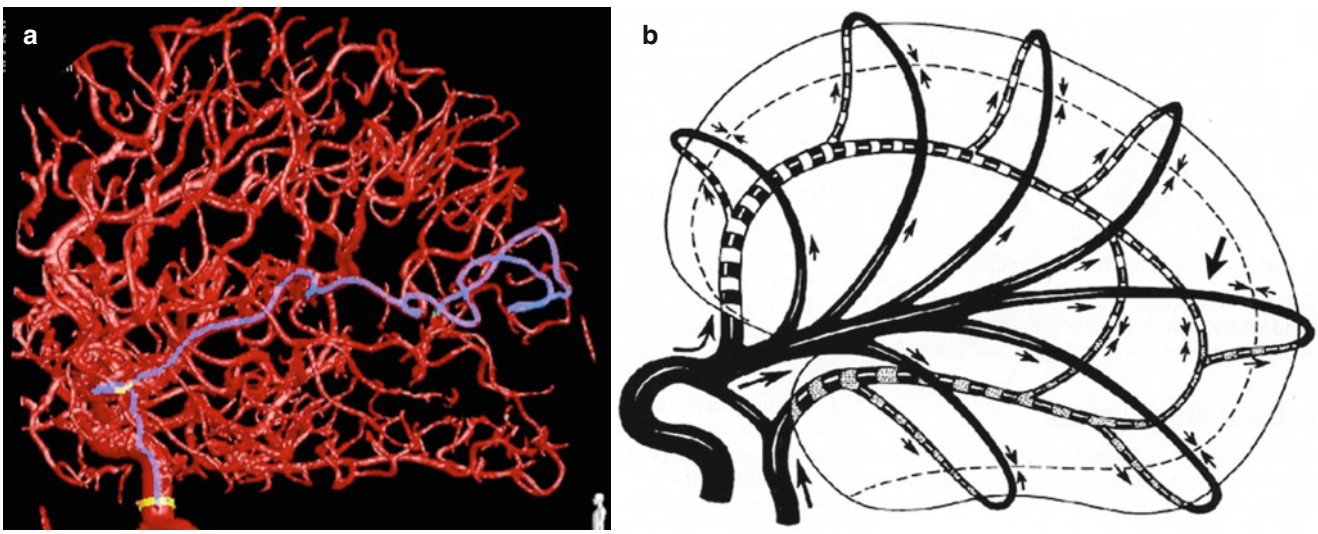

Fig. 8 (**a**, **b**) A 3D-RA lateral view and the schematic representation by Zurlch [15] demonstrating the potential anastomosis at the level of the cortical artery

fossa. However, superficial temporal artery-middle cerebral artery (STA-MCA) and superficial temporal artery-superior cerebellar artery (STA-SCA) bypass are relatively secure procedures with good patency compared to the occipital artery-posterior inferior cerebellar artery (OA-PICA) or PICA-PICA anastomosis [2, 13]. In certain situations such as the case presented here, bypass surgery is a less invasive procedure than the implantation of a stent in the elongated vessel with acute angle.

Prior to the sacrifice of the parent artery, it is necessary to evaluate hemodynamic tolerance [5, 11, 15]. As the functional evaluation of regional cerebral blood flow, a selective balloon occlusion test using a flexible microballoon catheter is reliable [5]. High-quality digital subtraction angiography (DSA), including not only the arterial phase but also capillary and venous phase, can delineate the regional cortical blood flow in detail and collateral circulation through the leptomeningeal anastomosis. If the distal territory of the target has poor collateral flow under the selective balloon occlusion test, EC-IC bypass or other modalities (e.g., intracranial stent) should be chosen. Additionally, it is very effective to confirm the function of the bypass before occluding the target vessel (Fig. 3).

Conclusion

Certain complex aneurysms may be treated optimally by combining endovascular and surgical procedures. Either endovascularly or surgically, precise hemodynamic evaluation using the selective balloon occlusion test based on the functional vascular anatomy is reliable and minimally invasive. Both modalities and team collaboration between bypass surgeons and endovascular surgeons are essential, especially in the management of intracranial fusiform aneurysm.

Conflict of Interest We declare that we have no conflict of interest.

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Analysis of Combined Coiling and Neuroendoscopy in the Treatment of Intraventricular Hemorrhage Due to Ruptured Aneurysm

Mitsutoshi Iwaasa, Tetsuya Ueba, Masakazu Okawa, and Tooru Inoue

Abstract *Background*: Subarachnoid hemorrhage (SAH) with intraventricular hemorrhage (IVH) is associated with poor outcomes. The aim of this study was to evaluate the effectiveness of combined coiling and neuroendoscopy to treat severe SAH with massive IVH.

Method: Between April 2008 and March 2012, 13 patients had massive IVH with a ruptured aneurysm treated at the Department of Neurosurgery, Fukuoka University, Japan. All 13 patients were treated within 2 days of onset by coiling and neuroendoscopic removal of the IVH, including the fourth ventricle.

Results: No rebleeding or acute hydrocephalus were noted. Glasgow Outcome Scale scores (GOS) at discharge were: good recovery (two patients), moderate disability (three patients), severe disease (one patient), vegetative state (four patients), and dead (three patients). A good modified Rankin Scale score (mRS) (0–2) at 6 months was observed in six patients and a poor mRS score (3–6) occurred in seven. The pre- and post-operative Graeb scores were significantly lower in the good mRS group ($p=0.020$ and 0.033, respectively, Mann-Whitney *U*-test). GOS scores at discharge were significantly associated with mRS score at 6 months ($p=0.011$, Fisher's Exact Test).

Conclusions: Combined coiling and neuroendoscopic removal of the IVH, including the fourth ventricle, were feasible procedures and achieved preferable outcomes in approximately half of the cases.

M. Iwaasa • T. Ueba, MD (✉) • M. Okawa, MD • T. Inoue, MD
Department of Neurosurgery,
Faculty of Medicine, Fukuoka University, 7-45-1 Nanakuma,
Jounan-ku, Fukuoka City, Fukuoka 814-0180, Japan
e-mail: tueba@fukuoka-u.ac.jp

Keywords Coiling • Neuroendoscopy • Intraventricular hemorrhage • Modified Rankin scale • Subarachnoid hemorrhage

Introduction

Patients with subarachnoid hemorrhage (SAH) accompanied by intraventricular hemorrhage (IVH) have poor outcomes [10, 17]. In these cases, two major problems must be urgently addressed: the increased intracranial pressure caused by the IVH and the risk of aneurysm rerupture.

Bilateral or unilateral ventricular drainage with aneurysmal clipping or coiling can be used to minimize secondary neuronal damage and the risk of aneurysm rupture [13]. Recently, studies reported that slow removal of the IVH by continuous ventricular drainage was insufficient [12, 14], and that radical removal gave preferable outcomes [2, 3, 6, 8, 9, 16]. We report a series of cases of severe SAH with massive IVH treated with a combination of coiling and neuroendoscopy.

Methods

Patient Population

We studied 13 SAH patients with massive IVH (WFNS clinical grade IV or V) treated in the Department of Neurosurgery, Fukuoka University, between April 2008 and March 2012. The inclusion criterion was the presence of massive IVH (Graeb score >6, with occlusion of the third and fourth ventricles). All patients were clinically evaluated using GCS score, and underwent three-dimensional CT angiography.

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The primary measured outcomes were the Glasgow Outcome Scale score (GOS) at discharge and the modified Rankin Scale score (mRS) after 6 months.

Statistical Analysis

The severity of IVH was graded using the Graeb scale [4]. Age and follow-up period (months) were considered continuous variables and analyzed by *t*-test. Gender, WFNS clinical grades, coiling first or endoscopy first procedure, and GOS scores were handled as categorical variables for Fisher's exact test. Pre- and postoperative Graeb scores were considered categorical variables for the Mann-Whitney *U*-test and Wilcoxon matched-pairs test. A p value of <0.05 was considered significant. Analyses were performed using SPSS 14.0.J (SPSS Inc., Chicago, IL, USA).

Neuroendoscopic Maneuvers

For neuroendoscopic removal of the IVH, a flexible endoscope (VISERA®, Olympus Medical Systems Corp., Tokyo, Japan) was used in all patients. The surgical approach was through frontal burr holes 2 cm anterior to the coronal suture and 2 cm from the midline. The direction of the trajectory to reach the ventricles using the Neuroport® (Olympus Medical Systems Corp., Tokyo, Japan) was towards the foramen of Monro. Aspiration through the working channel was alternated with rinsing with artificial cerebrospinal fluid (ARTCEREB®, Otsuka, Co., Ltd., Tokushima, Japan). After diligent aspiration and irrigation permitted complete clearance of the clots in the lateral ventricle, the clots of the aqueduct and fourth ventricle were also irrigated and aspirated. During this procedure, irrigation was isovolumetric as the clots occluded the outlets and the aqueduct was obstructed by the neuroendoscope.

Results

Coiling for the ruptured aneurysm and endoscopic removal of the IVH were performed uneventfully. Figure 1 shows a representative case of a ruptured internal carotid artery aneurysm. Within three postoperative days, all external drains were removed and patients underwent bedside rehabilitation. No rebleeding or delayed hydrocephalus requiring further external drainage was observed during the acute stage. Three patients died within 1 week because of acute brain swelling.

There were six patients in the better mRS (0–2) group and seven patients in the worse mRS (3–6) group. Table 1 shows the characteristics of our cases. There was no significant difference in terms of age, gender, WFNS clinical grade, coiling first procedure or endoscopy first procedure, or the follow-up period between the two groups.

GOS scores at discharge were significantly associated with mRS score at 6 months ($p=0.011$, Fischer's exact test).

After neuroendoscopic removal of the IVH, a significant reduction in the Graeb score (from 10.7 to 4.9) was observed ($p<0.001$, Wilcoxon paired *t*-test). Comparison of the better mRS group and the worse mRS group showed significant differences in the pre- and post-operative Graeb scores ($p=0.020$ and 0.033, respectively, Mann-Whitney *U*-test).

Discussion

Our study showed that neuroendoscopic removal of the IVH from the lateral to the fourth ventricle combined with coiling of the ruptured aneurysms was feasible, and could produce good outcomes in certain patients with severe SAH and massive IVH. Both the pre- and post-operative Graeb scores were significantly different between the better and the worse mRS groups, suggesting that increasing intracranial pressure was detrimental. This result may justify the endoscopic removal of clots in the fourth ventricle.

SAH patients with IVH show poor WFNS clinical grades, and poor outcomes [10, 17] and was almost doubled in one report [1]. IVH induces acute elevation of intracranial pressure, ischemic encephalopathy and secondary hydrocephalus [11]. Additionally, blood and its derivatives are clear proinflammatory agents and the cause of secondary neurological damage [7, 11]. Finding dense intraventricular clots on a CT scan has a very negative predictive value in patients with high-grade SAH [17]. Conventional management of IVH allows the IVH to remain in the ventricles for weeks [5], increasing the risk of infection. The combination of coiling and neuroendoscopic removal of IVH could minimize the risk of rebleeding and avoid proinflammatory agents and infection.

Longatti et al. [9] treated 10 SAH patients accompanied by IVH (WFNS clinical grade IV or V) using simultaneous coiling and endoscopic IVH removal, and obtained good outcomes. A report by Nishikawa et al. [15] also reported good outcomes.

Limitations of our Report

In our study, there was no significant difference between the coiling first procedure and the endoscopy first procedure. The association of the GOS score at discharge with the mRS score at 6 months could predict the long-term outcome.

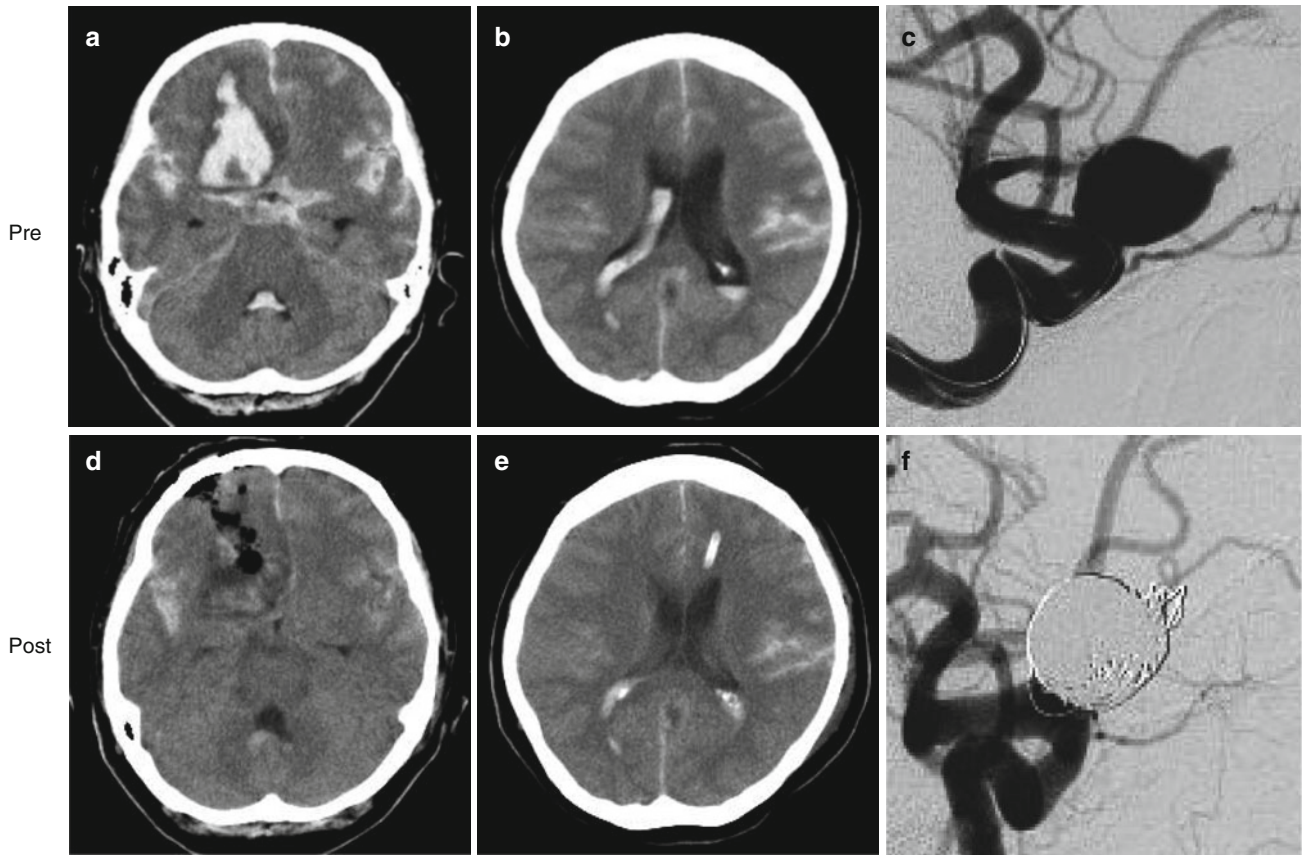

Fig. 1 A representative case. (**a, b**) CT performed on admission showing an SAH and massive IVH. (**c**) An internal carotid artery aneurysm is shown on angiography just before coiling (anterior-posterior view). (**d**, **e**) CT after successful removal of the IVH. (**f**) Angiographic appearance of the anterior communicating artery aneurysm after coiling (anterior-posterior view)

Table 1 Patient characteristics

Modified Rankin scale	0–2	3–6	*p*
Number	6	7	
Age (years)	60.7 ± 5.7	65.0 ± 6.1	NS[a]
Men:Women	3:3	3:4	NS[b]
WFNS Grade IV	1	0	
WFNS Grade V	5	6	NS[b]
Coil to endoscope	4	2	
Endoscope to coil	2	5	NS[b]
Preoperative Graeb score	10.3 ± 2.3	10.7 ± 1.5	0.020[c]
Postperative Graeb score	4.0 ± 2.3	5.3 ± 4.5	0.033[c]
GOS at discharge			
GR	2	0	
MD	3	0	
SD	1	0	
VS	0	4	
D	0	3	0.011[b]
Follow-up period (months)	16.8 ± 9.1	15.3 ± 8.6	NS[a]

WFNS World Federation of Neurological Surgeons, *GOS* Glasgow outcome scale, *GR* good recovery, *MD* moderately disabled, *SD* severely disabled,;*VS* vegetative state, *D* dead, *NS* not significant
[a]*t*-test
[b]Fischer's exact test
[c]*U*-test

However, careful interpretation of our results is necessary because of the small number of patients.

Conclusions

Radical removal of IVH from the lateral to the fourth ventricle appears to result in preferable outcomes for certain severe SAH patients with massive IVH. The combined treatment of coiling and neuroendoscopic removal of the IVH is a feasible therapy.

Conflict of Interest We declare that we have no conflict of interest.

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Intracranial Hypertension in Subarachnoid Hamorrhage: Outcome After Decompressive Craniectomy

D.T. Holsgrove, W.J. Kitchen, L. Dulhanty, J.P. Holland, and H.C. Patel

Absrtact Intracranial hypertension can occur following aneurysmal subarachnoid haemorrhage (SAH). It can be treated with decompressive craniectomy (DC) with the aim of reducing intracranial pressure, increasing cerebral perfusion and reducing further morbidity and mortality. We studied the outcome of patients undergoing DC following SAH at our institution, to ascertain whether the use of this treatment can be rationalized.

Keywords Subarachnoid hemorrhage • Intracranial hypertension • Decompressive craniectomy

Introduction

Raised intracranial pressure can occur following subarachnoid hemorrhage for a number of different reasons and at variable times after the ictus. Surgical treatment strategies to manage this problem include hematoma evacuation, CSF drainage and, in cases of refractory intracranial hypertension, DC (unilateral or bifrontal) can be considered. While outcome with this treatment has been, and still is, the subject of prospective randomized trials in trauma and also in ischaemia, less is known about its associated outcome following aneurysmal subarachnoid hemorrhage [1–3]. The aetiology of the raised pressure can determine the most appropriate treatment(s). We sought to identify whether the time from ictus or the aetiology of the raised pressure had an effect on outcome, with the aim of providing guidance for when to consider the use of DC in this patient group.

D.T. Holsgrove (✉) • W.J. Kitchen • L. Dulhanty
J.P. Holland • H.C. Patel
Department of Neurosurgery, Salford Royal Hospital,
Manchester M6 8HD, UK
e-mail: daniel.holsgrove@srft.nhs.uk

Materials and Methods

Our database of patients admitted with SAH and our operating theater records were examined to determine which patients had undergone a decompressive craniectomy. Those included were diagnosed with SAH using computed tomography (CT) or lumbar puncture and had aneurysms confirmed with the use of either CT and/or digital subtraction angiography (DSA). The electronic patient records system was used to retrieve medical records for clinical information, including outcome assessment, and the Picture Archiving and Communications System (PACS) to review patients' scan images and reports.

It was determined that those undergoing DC had raised intracranial pressure (ICP), either by intra-operative assessment by the surgeon at the time of microsurgical clipping, or using intra-parenchymal monitoring in the intensive care unit (either Codman ICP Monitoring System, Codman & Shurtleff, Inc, USA or Raumedic NEUROVENT-P-TEMP Monitor, Raumedic AG, Germany).

Patients undergoing DC have been subdivided into those with and those without a hematoma requiring evacuation as part of the procedure.

Results

During the four-year period from January 2007 to December 2010, 665 patients were admitted with aneurysmal SAH, of whom 607 underwent treatment for their aneurysm(s). Of these 607 patients, 117 (19.3 %) underwent microsurgical clipping and 490 (80.7 %) underwent endovascular coiling. Decompressive hemi-craniectomies were performed in 20 patients, with two of them undergoing bifrontal decompressive craniectomies following SAH. The pathway to decompression varied within the group, with some undergoing decompression at the time of aneurysm treatment, others prior to it, and some in a delayed fashion.

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Table 1 Patient characteristics and treatment method

		All patients	Hematoma evacuated	No Hematoma evacuated
Number		22	13	9
Age (median)		43.1	50.6	40.3
Sex (F:M)		14:8	9:4	5:4
WFNS grade N (%)	1	2 (9)	0	2 (22)
	2	1 (5)	1 (8)	0
	3	1 (5)	1 (8)	0
	4	8 (36)	6 (46)	2 (22)
	5	10 (45)	5 (38)	5 (56)
Aneurysm treatment N (%)	Clip	11 (50)	8 (61.5)	3 (33)
	Coil	9 (41)	4 (30.8)	5 (56)
	None	2 (9)	1 (7.7)	1 (11)

Table 2 Outcome following SAH and decompressive craniectomy

	All patients	Hematoma evacuated	No hematoma evacuated
GOS	N (%)	N (%)	N (%)
1	11 (50)	6 (46.2)	5 (56)
2	0	0	0
3	4 (18)	3 (23.1)	1 (11)
4	2 (9)	2 (15.4)	0
5	5 (23)	2 (15.4)	3 (33)

Table 1 shows the patients' characteristics subdivided into those with and those without a hematoma evacuated at the time of DC. There was a median age of 43.1 and a preponderance of females. The majority who underwent a DC were admitted with a poor WFNS grade. This is not an unexpected finding given that this measure is usually utilized in those with a life-threatening hematoma or uncontrollable ICP, which are more likely to be observed in those admitted with a worse clinical grade. A higher proportion of those undergoing hematoma evacuation in addition to decompression had their aneurysms clipped rather than coiled, which was the reverse of the group with no hematoma evacuated.

Table **2** shows the Glasgow Outcome Scale (GOS) for those patients who underwent a DC, including the breakdown by whether the surgery included hematoma evacuation. This demonstrates a wide variability in outcome in the two subgroups in addition to the total patient group. There was no statistical significance in outcome between the two subgroups ($p=0.63$). The outcome (GOS 1–3 = poor and 4–5 = good) when measured against the time from ictus to decompression, as seen in Fig. **1**, also did not show a statistical significance ($p=0.762$).

The median follow-up was 1 year (range 6.5–16.3 months) in survivors. All deaths occurred within 30 days (median of 7 days, range 1–90) except for one, which occurred 3 months after the subarachnoid hemorrhage.

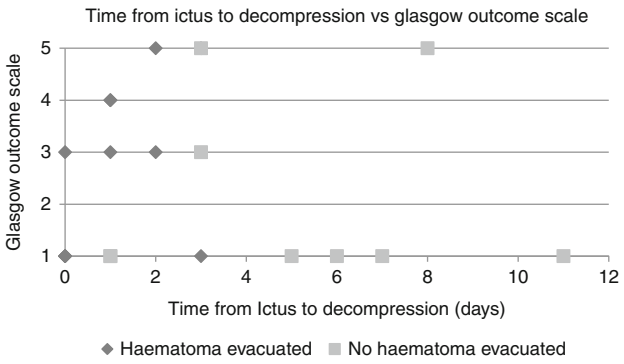

Fig. 1 Scatter graph demonstrating outcome for the two subgroups

The size of the craniectomy performed varied, with the maximum diameter being larger than 12 cm in 10 of 22 patients, smaller than 12 cm in 9, and unknown in 3. There was no significant difference in outcome based upon the whether the bone flap was larger or smaller than 12 cm ($p=0.78$).

A relationship was identified whereby worse WFNS grades were associated with poorer outcomes ($p=0.04$). However, patient age did not have a significant association with outcome in this series ($p=0.61$).

Discussion

This group of 22 patients with SAH and undergoing DC demonstrates a wide variance in outcome. No significant difference was observed in either of the two subsets with and without hematoma evacuation, or with time of ictus to decompression. However, there was an association between WFNS grade and outcome. There have been a number of other case groups of patients undergoing DC after SAH that have identified other significant variables affecting outcome.

A study of 16 patients by Clemens et al. showed a significant difference in outcome for those undergoing early DC (<48 h after ictus) with 6 of 8 patients having a good outcome, compared to only 1 of 8 in whom late decompressions were performed [4]. However, the larger case series of 79 patients undergoing decompressive craniectomies after SAH, by Guresir et al., found that it was the time from ICP becoming elevated to decompression rather than from the ictus that provided a significant difference in outcome [5]. In this paper, no significant difference was observed between those undergoing primary versus secondary decompression, and those with brain swelling alone versus bleeding or infarction.

This was in contrast to the group of Dorfer et al., which consisted of 66 patients undergoing DC following SAH. This study found that timing was not a significant factor in predicting outcome, but that there was a difference in outcome depending on the pathology necessitating DC. There was a significantly better neurological outcome in those with a hematoma compared to those with ischaemia [6].

Timing was a significant factor related to outcome in the trials on DC for malignant MCA infarction [3]. The difference in aetiology amongst those undergoing DC following SAH (hematoma, early swelling, delayed ischaemia) may explain why the studies on DC after SAH have not consistently had the same findings. The subset undergoing DC after SAH for ischaemia do not usually have a clear point in time when the ischaemia begins, unlike those in the trials for DC after malignant infarction, which again makes comparisons inappropriate.

It has been previously shown that a larger craniectomy is significantly related to a decrease in intracranial pressure and better outcome [7]. This was not demonstrated in our patient group but the sample may have been subject to selection bias. Some patients underwent surgery for a planned DC following failure of all other treatment modalities to control ICP, whereas others had it performed due to swelling encountered at the time of aneurysm clipping early in their admission. The different operative approach may have influenced the size of the craniectomy performed. A retrospective analysis of 525 decompressive craniectomes performed in seven neurosurgical centres found that only 43 % had bone flaps >12 cm removed. This again, may have been due to a large number in this study undergoing primary decompressions associated with hematoma evacuations. In this study it was found that there was a better outcome in those under the age of 65 undergoing DC with a bone flap >12 cm, although this included other causes, in addition to SAH, for the intracranial hypertension [8].

Our study has demonstrated that some patients can have a good outcome despite their poor clinical state prior to DC. DC following SAH is used rarely used (22 of 665 cases (3.3 %) of SAH over a four year period), which makes analysis of its outcome and associated factors difficult due to the large number of patient variables. While it is clear that a good outcome can be achieved, the majority were not so fortunate, with 50 % of our cohort dying and 18 % being left with a severe disability. There has been variability in the findings from other groups, which may be due to the relatively small numbers and varying indications for DC within this patient group.

Conclusion

A number of different factors have been shown to influence outcome following DC after SAH (WFNS grade, aetiology of intracranial hypertension, timing of surgery). However, study findings have not consistently been replicated. Some patients do appear to benefit from DC following SAH but it would still be difficult, using the studies published so far, to predict outcome accurately enough to determine whether the treatment should be recommended.

Conflict of Intrerest We declare that we have no conflict of interest.

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Cerebral Revascularization

Selective Targeted Cerebral Revascularization via Microscope Integrated Indocyanine Green Videoangiography Technology

Giuseppe Esposito and Luca Regli

Abstract Protective or flow replacement bypass surgery has an important role in the management of complex middle cerebral artery (MCA) aneurysms. Protective bypass is useful when prolonged temporary arterial occlusion is needed for clip reconstruction. Flow replacement bypass is instead important when aneurysmal trapping is the treatment of choice in order to supply permanent collateral blood flow to the brain distal to the "trapped" vessel. In both cases, the identification of the correct recipient artery is an essential surgical step. When a superficial (cortical) artery is chosen as recipient, it indeed has to represent a distal branch of the involved (temporarily or permanently occluded) vessel.

Here we describe a technique for selective-targeted revascularization based on the use of indocyanine green video angiography (ICG-VA), a microscope-integrated intraoperative tool nowadays known to provide real-time assessment of the cerebral circulation with distinct visualization of arterial, capillary and venous angiographic phases. The technique is founded on the analysis of differences in the timing of filling of M4 vessels seen on serial ICG-VAs. It enables reliable identification of the cortical recipient and eliminates the risk of erroneous revascularization of non-involved territories. The surgical decision-making of two patients treated for complex MCA aneurysms with selective-targeted bypass is presented.

Keywords Cerebral revascularization • Complex aneurysms • Indocyanine green video angiography, ICG-VA • MCA aneurysms • Bypass recipient artery • Selective EC-IC bypass • STA-MCA bypass

G. Esposito, MD (✉) • L. Regli, MD
Department of Neurosurgery, University Hospital Zurich, Frauenklinikstrasse 10, CH-8091 Zurich, Switzerland
e-mail: giuseppe.esposito@usz.ch

Abbreviations

CT	Computed tomography
CT-A	Computed tomography angiography
DSA	Digital subtraction angiography
EC-IC	Extra-to-intracranial
ICG	Indocyanine green
ICG-VA	Indocyanine green video angiography
MCA	Middle cerebral artery
STA	Superficial temporal artery
STA-MCA	Superficial temporal artery to middle cerebral artery

Introduction

Complex MCA aneurysms not amenable to selective clipping or coiling are frequently treated by clip reconstruction or by aneurysm trapping. In these cases, respectively, a protective or a flow replacement bypass is important in order to avoid ischemic consequences. In fact, a protective bypass is useful when a prolonged arterial occlusion (parent artery or aneurysmal branch) is necessary for a safe clip reconstruction, while a flow replacement bypass permits supplying collateral blood flow to the brain distal to a permanently occluded (trapped) vessel [7, 9, 10, 13, 14].

When microsurgical dissection of the peri-aneurysmal angioanatomy can be safely performed, the selection of a recipient artery among the vessels exposed within the dissected Sylvian fissure is a valid option – for instance, an M2 or M3 segment of the MCA [10]. When dissection of the Sylvian fissure is considered more difficult or risky, or when avoiding a deep site for the anastomosis is preferred, a superficial cortical recipient artery (namely, an M4 segment of MCA) can be chosen as recipient instead [5, 14]. Because the goal of the bypass is the preservation of blood flow in the area fed by the vessel that needs to be occluded for final aneurysm treatment (temporarily or permanently), it is very

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important that the recipient artery indeed represent a distal branch of the trapped vessel [5, 9, 12, 14].

Despite the use of angioanatomical landmarks, neuroimaging, neuronavigation and stereotactic modalities [2, 4, 8] to identify the correct recipient, the risk of revascularization into a wrong area still exists. Revascularization of the wrong area would obviously lead to possible severe ischemic effects [2, 5, 14].

In this article we describe a technique for the selective identification of a cortical (M4) recipient artery during extra-to-intracranial (EC-IC) bypass surgery. The technique is based on the use of microscope-integrated near-infrared ICG-VA that is known as a reliable and non-invasive technique introduced in neurosurgery for intraoperative observation and documentation of blood flow of large and small vessels [3, 11]. We recently reported this technique when describing our experience in treating seven patients with complex MCA aneurysms; three illustrative cases were presented [5]. Here we further describe the possible application of the technique and illustrate the cases of two other patients.

Materials and Methods

Patients

The surgical decision-making for two patients treated for complex MCA aneurysms with selective-targeted EC-IC bypass is reported. The patients underwent pre-operative neuroimaging consisting of a computed tomography (CT) scan, CT-angiography (CT-A) and digital subtraction angiography (DSA) with 3D reconstructions in order to optimally define the peri-aneurysmal angioanatomy. Control angiography (CT-A or DSA) was performed in the first 72 h after surgery. In one patient (Illustrative Case #2), a radiological angiographic follow-up was done at 3 months as well. The functional health of the two patients was assessed preoperatively and at the 3-month follow-up.

Intraoperative Microscope Integrated ICG-VA

A standard indocyanine green (ICG) dose of 25 mg dissolved in 5 ml water was injected into a central vein as a bolus, so the field of interest was illuminated with near-infrared light emitted by a commercially available surgical microscope (OPMI® Pentero™, Carl Zeiss Co., Oberkochen, Germany). The ICG-VA video was recorded for further analysis. ICG-VA is repeated as many times as needed within the daily dose limit of ICG (5 mg/kg), waiting at least 10 min between two consecutive intravenous ICG injections.

Identification of the Recipient Artery

Real-time ICG-VA is used for the visualization and analysis of the cortical vasculature at the craniotomy site as well as for the distinct evaluation of arterial, capillary and venous phases of cortical peri-Sylvian fissure vessels, with excellent image quality, spatial and temporal resolution [3, 11]. The presented technique for selective targeted bypass is based on the analysis of the difference in timing of the fluorescence of M4 cortical vessels seen on serial ICG-VAs.

A delayed (asymmetric) fluorescence of cortical M4 vessels may be visualized either primarily (on a baseline ICG-VA) or secondarily (on a provoked ICG-VA, after temporary occlusion of the aneurysm parent artery or an aneurysmal branch). These situations are called, respectively, primary and secondary identification (see Table 1).

M4 branches presenting (primarily or secondarily) delayed fluorescence represent suitable bypass recipient arteries. Among these cortical M4 branches, the most suitable recipient is chosen on the basis of microsurgical criteria (e.g., length, width, absence of side branches).

After the bypass is performed and the aneurysmal lesion is treated (either by clip reconstruction or by partial/complete trapping), a final ICG-VA is expected to show symmetric/simultaneous fluorescence of the peri-Sylvian fissure cortical arterial (M4) branches. A flow chart illustrating the technique is presented in Fig. 1.

Furthermore, this technique can be applied to identify "uninvolved" cortical arteries, namely peri-Sylvian fissure cortical arteries not representing distal branches of the artery that need to be occluded for the final aneurysmal treatment. This step could be useful for further verification – for instance, in the case of a complex aneurysm of MCA bifurcation, where the cortical branches of an anterior temporal artery (that arises before the first MCA bifurcation) have to be excluded as possible recipients. This strategy is illustrated in the flow chart in Fig. 2.

Table 1 Primary and secondary identification of cortical recipient artery in selective targeted revascularization using of ICG-VA technology

Primary identification	A delayed (asymmetric) fluorescence can be primarily seen on the baseline ICG-VA. In this case, no temporary occlusion of arteries is performed. Such a delay can be caused either by stenosis/occlusion of an aneurysmal branch or increased resistance to flow (i.e., turbulent flow in the aneurysm, the presence of a serpiginous aneurysm).
Secondary identification	A delayed (asymmetric) fluorescence can be secondarily detected after provocative ICG-VA, performed after temporary occlusion of the aneurysm parent artery or any aneurysmal branch (that may need to be temporarily or permanently occluded for final aneurysmal treatment).

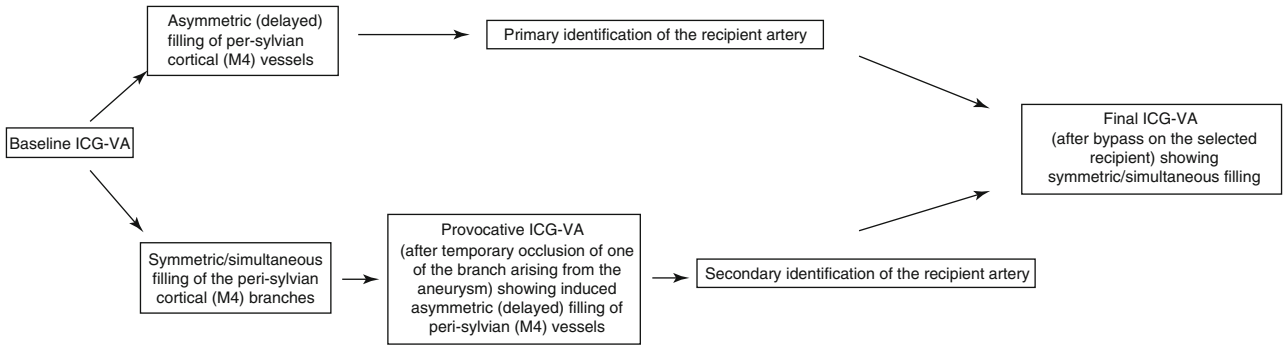

Fig. 1 Flow chart illustrating the steps for intraoperative identification of the correct recipient using ICG-VA technology

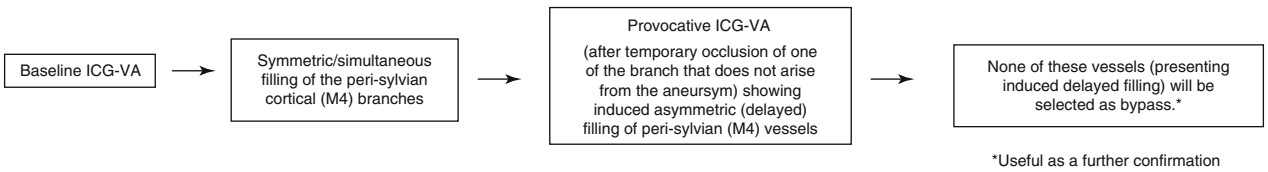

Fig. 2 Flow chart illustrating the steps for intraoperative exclusion of erroneous cortical recipients using ICG-VA technology

Further proof of the correct revascularization may be obtained by using intraoperative flowmetry, because the flow in MCA branch/branches that undergo occlusion (temporarily or permanently) for final aneurysm treatment has to match the flow provided by the bypass.

Results

Two illustrative cases are presented. These patients underwent successful treatment of the aneurysm using selective targeted revascularization via ICG-VA technology. The application of the proposed technique allowed reliable identification of the correct recipient artery (cortical branches of the involved MCA segment) and permitted bypassing the correct area in both patients. After bypass and final aneurysm treatment, the peri-Sylvian fissure vascular area fluoresced concomitantly (symmetrically and simultaneously) on the final ICG-VA. No complications occurred, whether due to multiple serial intravenous ICG administrations or due to the temporary occlusion time needed for the provocative ICG-VA (that was always less than 2 min). There were no ischemic complications and patients had no neurological deficits, either after surgery or after the 3-month follow up.

Illustrative Case #1

A 48-year-old man was admitted for the treatment of a calcified partially thrombosed sub-giant MCA aneurysm (M1 bifurcation) and of a small anterior choroidal artery aneurysm (Fig. 3a–d). Upon admission, the neurological examination was normal. During surgery, the right parietal and frontal branch of the superficial temporal artery (STA) were dissected, and a right pterional craniotomy was then performed. After opening the dura, the aneurysm was visible at the surface of the Sylvian fissure that was so progressively opened by means of microsurgical techniques. The large thrombosed sac did not allow for safe dissection of the MCA bifurcation and the proximal part of the M2 branches. We therefore decided to perform a superficial temporal artery to middle cerebral artery (STA-MCA) bypass, using a cortical (M4) branch of the larger inferior M2 segment as a recipient. To avoid erroneous revascularization, the ICG-VA-assisted technique for selective revascularization was applied as follows:

After a baseline ICG-VA was obtained to study the cortical peri-Sylvian fissure angioanatomy, a temporary clip was placed on the larger inferior M2 segment and a new provocative ICG-VA was performed. A cortical area showing delayed fluorescence was clearly evident (Fig. 3e): arteries in this zone fluoresced (through retrograde revascularization) during the normal venous phase of the rest of the analyzed peri-Sylvian cortical vasculature (Fig. 3f). The best suitable cortical artery within this area (see arrows in Fig. 3f, g) was chosen as recipient and a "protective" STA-MCA bypass was then performed. Therefore we considered the exploration of the aneurysm to be safe because the protective bypass supplied the flow to the larger M2 territory, in case of prolonged temporary occlusion. With temporary M1 occlusion, we proceeded with intra-aneurysmal thrombus removal until sharp backflow bleeding was seen through the opened aneurysm. Temporary clips were shortly placed on the M2 trunks in order to safely complete the thrombectomy/endarteriectomy and to effectively reconstruct the aneurysmal base by clips preserving the permeability of the MCA bifurcation and both M2 segments.

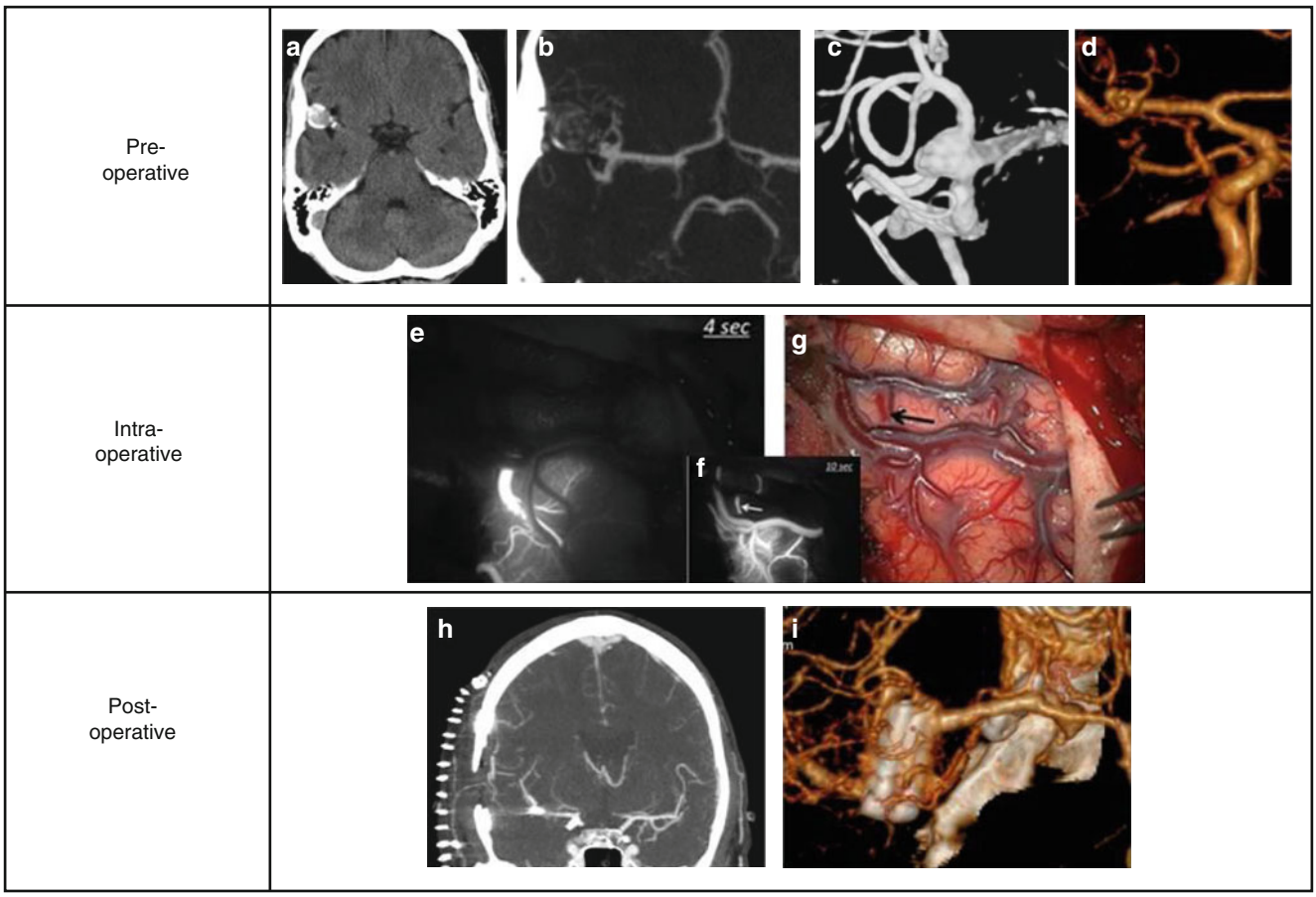

Fig. 3 Pre-operative CT (**a**), CT-A (**b**) and 3-dimensional DSA (**c**) documenting a calcified partially thrombosed sub-giant aneurysm of M1 bifurcation and a small anterior choroidal artery aneurysm (**d**). Provocative ICG-VA (after temporary occlusion of the inferior M2 trunk) showing asymmetric fluorescence (delayed cortical filling) of a peri-Sylvian fissure area (**e**). Within this area (whose arteries took fluorescence during the venous phase of the videoangiography – see **f**), the best suitable cortical artery is targeted as a recipient, based on microsurgical criteria (see *arrows* in **f** and **g**). Post-operative CT-A documenting bypass patency (**h**) and exclusion of the two aneurysms (**i**)

All the temporary occlusions were performed under induced hypertension and under the protection of the STA-MCA bypass. Finally, the anterior choroidal artery aneurysm was clipped as well. A final ICG-VA showed patency of the bypass and symmetric fluorescence of the peri-Sylvian fissure cortical arteries. Upon awakening, no neurological deficits were reported. Post-operative neuroimaging (CT-A) performed 72 h after surgery exclusion of the two aneurysms and (i) patency of the bypass (Fig. 3h), despite the fact that it had competitive anterograde flow and exclusion of the two aneurysms. At the 3-month clinical follow-up, the neurological examination was normal. No further radiological follow-up was done since the bypass was a protective bypass and the aneurysms exclusion had already been confirmed 3 days post-operatively.

Illustrative Case #2

A 32-year-old man was diagnosed with a fusiform right MCA aneurysm of the M2 bifurcation (Fig. 4a–c). The origin of the aneurysm was bacterial, stemming from endocarditis. During surgery, the parietal STA branch was dissected and a pterional craniotomy performed. After opening the dura, dissection of the Sylvian was found to be extremely difficult and risky, due to post-inflammatory dense arachnoidal adhesions between the intra-Sylvian vessels. We therefore decided to avoid total opening of the fissure because of the high risk of vascular injury and to treat the aneurysmal lesion by partial trapping (inflow proximal occlusion) in association with an STA-MCA bypass (to revascularize the area fed by the aneurysmal artery). Flow measurement of the aneurysmal parent vessels was 32 ml/min. To identify a suitable cortical recipient (M4 segment), the ICG-VA-assisted technique for selective targeted revascularization was used. After a baseline ICG-VA, a provocative ICG-VA was performed after positioning a temporary clip on the aneurysm parent artery; asymmetric fluorescence around the Sylvian fissure was evident, with a peri-Sylvian fissure area clearly presenting with a delayed filling. The best suitable arterial recipient found in this area was chosen as recipient. After removal of the temporary clip on the aneurysm parent artery, the bypass was performed (flow measurement = 11 ml/min). A definitive final clip was then placed

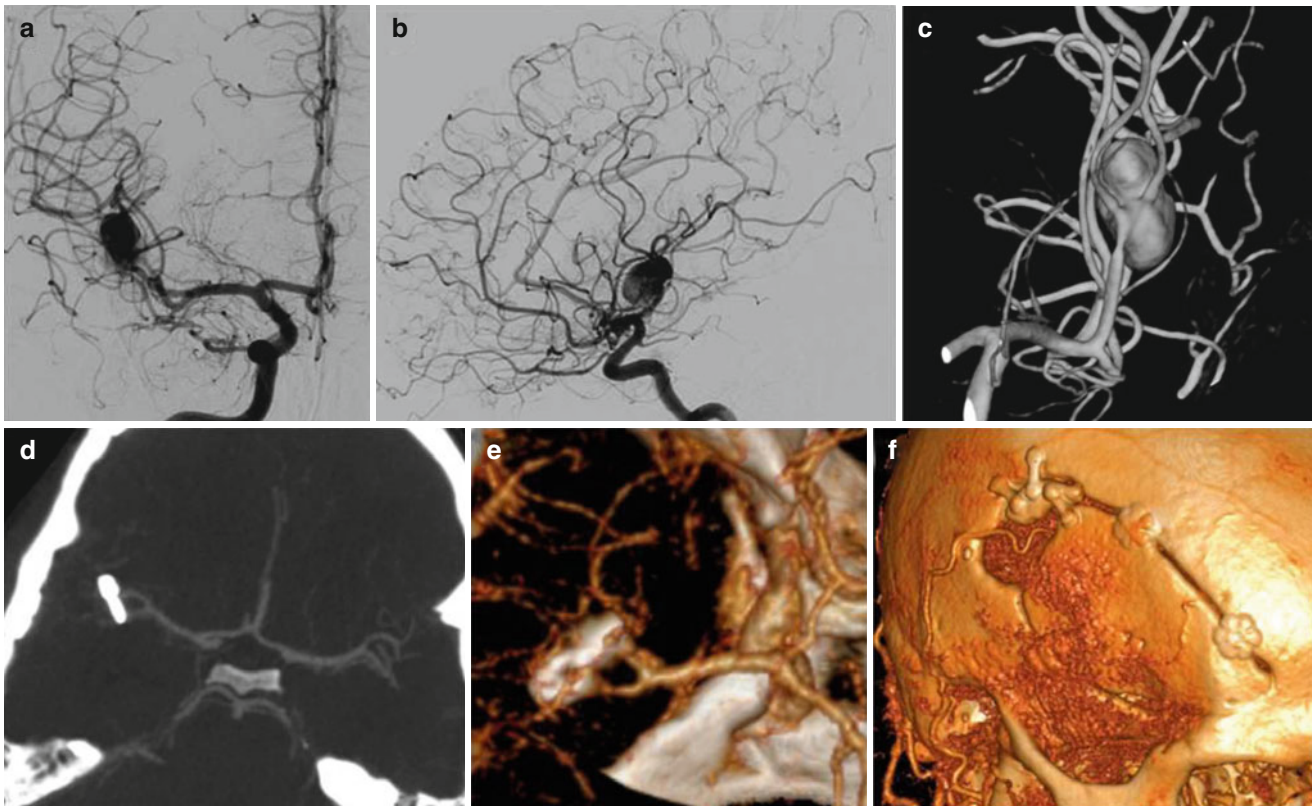

Fig. 4 Pre-operative DSA (**a**, **b**) with 3-D reconstruction (**c**) showing a right fusiform MCA aneurysms (M2 bifurcation). Post-operative CT-A documenting aneurysm exclusion (**d**, **e**) and patency of the right STA-MCA bypass (**f**)

on the M2 branch just proximal to the aneurysm, after which the bypass flow increased to 29 ml/min. A final ICG-VA showed patency of the bypass and symmetric fluorescence of the peri-Sylvian fissure cortical arteries. Upon awakening, the patient had no new neurological deficits. Post-operative CT-A 72 h after surgery documented aneurysm exclusion (see Fig. 4d, e) and patency of the STA-MCA bypass (Fig. 4f). At the 3-month follow-up, a new CT-A confirmed the previous radiological results and the neurological examination was normal.

Discussion

Both protective and flow-replacement EC-IC bypass surgery represent a very important tool for the treatment of complex MCA aneurysms [7, 9, 10, 13, 14]. The aim of the bypass is obviously the preservation of brain perfusion. When a cortical artery is preferred as recipient, its identification is a crucial surgical step. In fact, the bypass has to match the distal area of the involved vessel; in other words, the recipient indeed has to represent a branch of the occluded MCA branch. In this way, either prolonged temporary or permanent occlusion can be executed with minimal ischemic risk. Both combined endovascular/microsurgical [1, 6] or purely microsurgical [5–12] techniques to correct identify the recipient artery in bypass surgery have recently been reported.

We had already introduced this ICG-VA-based technique for selective revascularization in a previous paper. We presented the cases of 7 patients treated for complex MCA aneurysms with selective-targeted EC-IC bypass and described three cases in detail. The technique was shown to allow the correct identification of cortical recipient vessels in selective-targeted EC-IC bypass surgery and to eliminate the risk of the revascularization of erroneous cortical territories [5]. In this article we further describe the possible applications of this technique for selective revascularization and illustrate the surgical decision-making of two patients treated for complex MCA aneurysms.

As shown, the technique is essentially based on the analysis of fluorescence of peri-Sylvian fissure M4 vessels before (baseline ICG-VA) and during temporary clipping (provocative ICG-VA) of any MCA branch whose occlusion is needed for final aneurysm treatment. The provocative ICG-VA is able to show asymmetric fluorescence among peri-Sylvian fissure vascular arterial areas, namely, an area presenting a delayed cortical filling. M4 vessels in the area presenting delayed fluorescence activity represent suitable recipients and the best recipient artery can be selected based on conventional microsurgical criteria such as location, size, length, presence of perforators, etc.

In the two patients reported on, the information provided by ICG-VA technology allowed the correct identification of

the cortical recipient. Both patients underwent successful treatment of their aneurysms, no ischemic complications were reported, and a favorable clinical outcome was achieved in both cases.

This technique enables reliable and accurate identification of the cortical recipient artery and eliminates the risk of revascularization of erroneous areas. It is efficient and can be applied in managing either proximal or distal complex MCA aneurysms. The technique can also be considered as a step towards reduced invasiveness. In fact, a superficial (cortical) bypass is easier, less invasive and safer than a proximal deep one – easier, because working in a deep and narrow operative corridor is definitely more challenging than working on the cortex; less invasive, because it enables reliable targeting of a cortical recipient without the need for dissection of MCA branches along the Sylvian fissure to the cortex; and safer because the tolerance to ischemia is better during the temporary occlusion of a cortical M4 branch as compared with the occlusion of a more proximal M2 or M3 segment. Limitations of this technique essentially consist of the increased operative time (10–20 min more), because of the time interval needed between serial ICG-VA runs and the slight temporary occlusion time for the provocative ICG-VA. However, considering the fact that this temporary occlusion time was always less than 2 min, it can be largely accepted in the treatment of complex MCA aneurysms [7, 9, 10].

Conflict of Interest We declare that we have no conflict of interest.

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Combined Bypass Technique for Contemporary Revascularization of Unilateral MCA and Bilateral Frontal Territories in Moyamoya Vasculopathy

Annick Kronenburg, Giuseppe Esposito, Jorn Fierstra, Kees P. Braun, and Luca Regli

Abstract Moyamoya vasculopathy (MMV) leads to chronic hypoperfusion predominantly in the middle cerebral artery (MCA) and anterior cerebral artery (ACA) territories. Most revascularization techniques focus on revascularization of the MCA territory. Augmentation of blood flow in the frontal area is important for neurocognition and lower extremity function. In this article we describe a new combined (direct and indirect) one-stage bypass technique consisting of a superficial temporal artery to middle cerebral artery (STA-MCA) bypass with encephalo-duro-synangiosis (EDS) for unilateral MCA revascularization, along with an encephalo-duro-periosteal-synangiosis (EDPS) for bifrontal blood flow augmentation. The strength of this technique is the revascularization of three vascular territories during a single surgical intervention: the MCA unilaterally; and the frontal territories bilaterally. Bifrontal EDPS may also be considered as a supplementary independent procedure for patients who previously underwent revascularization treatment in the MCA territory, but develop symptoms due to frontal hypoperfusion.

Keywords Bilateral frontal territories • Bypass surgery • STA-MCA bypass • Indirect revascularization • Moyamoya • Neurocognition

Abbreviations

ACA	Anterior cerebral artery
CBF	Cerebral blood flow
CVR	Cerebrovascular reserve
EDS	Encephalo-duro-synangiosis
EDMS	Encephalo-duro-myo-synangiosis
EMS	Encephalo-myo-synangiosis
EDPS	Encephalo-duro-periosteal-synangiosis
EPS	Encephalo-periosteal-synangiosis
$[^{15}O]H_2O$-PET	$[^{15}O]H_2O$-positron emission tomography
ICA	Internal carotid artery
IF	Interhemispheric fissure
MCA	Middle cerebral artery
MMD	Moyamoya disease
MMS	Moyamoya syndrome
MMV	Moyamoya vasculopathy
SSS	Superior sagittal sinus
STA	Superficial temporal artery
TIA	Transient ischemic attack

Introduction

Moyamoya disease (MMD) is a rare cerebrovascular disease of unknown etiology that is characterized by progressive bilateral stenosis of the intracranial internal carotid arteries (ICAs) and their proximal branches, resulting in cerebral hypoperfusion with subsequent ischemic symptoms or, less often, intracerebral hemorrhage [14, 21]. If moyamoya vasculopathy (MMV) is associated with other conditions (i.e., Down's syndrome, neurofibromatosis type I), patients are diagnosed as having moyamoya syndrome (MMS) [21].

In MMV, reduced cerebral perfusion leads to compensatory development of collateral vasculature by small vessels near the apex of the carotid, on the cortical surface, leptomeninges, and branches of the external carotid artery supplying the dura and the skull base; these processes rarely involve the posterior circulation [22]. Surgical cerebral revascularization is considered to be the only effective treatment modality and can be achieved by direct, indirect or combined methods [1, 3, 14]. Direct techniques consist of an anastomosis of a donor artery, generally the superficial

A. Kronenburg, MD • K.P. Braun, MD, PhD
Department of Neurology and Neurosurgery,
Brain Center Rudolf Magnus, UMC Utrecht,
85500, Utrecht 3508 GA, The Netherlands
e-mail: a.kronenburg@umcutrecht.nl

G. Esposito, MD (✉) • J. Fierstra, MD • L. Regli, MD, PhD
Department of Neurosurgery, University Hospital Zürich,
Frauenklinikstrasse 10-CH-8091,
Zürich, Switzerland

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temporal artery (STA), to a cortical recipient arterial branch of the middle cerebral artery (MCA), which instantly augments blood supply. Indirect methods for cerebral revascularization are based on the approximation of vascularized tissue such as the temporal muscle, pericranium, dura or omentum onto the cortex in order to promote neoangiogenesis over time [1, 4]. Combined techniques provide the advantages of both methods; however, there is no evidence of one technique having advantages over the other [3]. Most techniques focus on revascularization of the MCA territory, yet revascularization in the frontal territory is gradually receiving more attention: part of the ischemic presentation of (pediatric) moyamoya patients consists of neurocognitive disorders as well as lower extremity function, caused by frontal hypoperfusion [2, 5, 12, 24]. Re-establishing cerebral blood flow (CBF) in the frontal territory may prevent, stabilize or improve neurocognitive decline [6, 7, 15, 17–20, 24].

In this paper, we describe a combined one-stage procedure for revascularization of the MCA territory unilaterally by a direct STA-MCA bypass and encephalo-duro-myosynangiosis (EDMS) and the bifrontal territory by an encephalo-duro-periosteal-synangiosis (EDPS). To illustrate the procedure, the treatment of a girl affected by MMS is reported.

Materials and Methods

Illustrative Case

A 9-year-old girl affected by neurofibromatosis type I presented with multiple transient ischemic attacks (TIAs) consisting either of diplegia of the legs or monoparesis of the left arm, combined with frequent headaches. Neurological examination showed no deficits. Neuroimaging (MRI, MRA and DSA) demonstrated bilateral occlusion of the terminal ICA and the M1 and A1 segments, with bilateral typical compensatory moyamoya vessels. The patient was diagnosed as having MMS. An [^{15}O]H_2O-positron emission tomography ([^{15}O]H_2O-PET) scan documented extensive decreased baseline CBF in the right MCA and frontal area as well as severely impaired cerebrovascular reserve (CVR) in almost the entire right hemisphere after the administration of acetazolamide. Moderately decreased baseline CBF was seen in the left hemisphere, especially the frontal area, with well-preserved CVR in the MCA and posterior cerebral artery territory, but decreased frontal CVR (Fig. 1a, c). Based on the symptomatic course of the disease and the hemodynamic insufficiency, surgical revascularization was indicated and aimed at increasing the blood supply to the right MCA and frontal territories.

Combined Technique for Unilateral MCA and Bifrontal Revascularizazion

After general anesthesia, the patient was placed in the supine position with the head mildly extended and rotated 30° to the left in a Mayfield headrest. The first procedure step consisted of a right-sided STA-MCA bypass along with EMS. A linear incision located behind the hairline over the course of the STA was performed, without shaving the hair. The classic technique of an STA-MCA bypass was followed [9]. The parietal branch of the STA was dissected and the small branches arising from the STA were coagulated and cut. The donor vessel was kept intact until the anastomotic procedure was started. The temporal muscle was dissected and cut along the skin incision and a craniotomy was performed along the Sylvian fissure. The dura mater was thereafter carefully opened in a star fashion to maintain the main branches of the middle meningeal artery; dural flaps were reflected over the brain surface underneath the bone window and EDS was obtained by creating contact between the external surface of the dura and the brain surface. Afterwards, the cortex was surveyed for the largest cortical recipient artery. After identification of the most suitable recipient vessel, it was dissected by means of an arachnoid opening. A temporary non-traumatic microvascular clip was placed across the proximal exposed STA. A fish-mouth cut was then executed at the distal STA to increase the donor vessel's opening diameter. The STA was passed through a small cut performed in the temporal muscle (in order to allow its intracranial entrance, with no risk of compression). A blue dye was put onto the surface of the cutting edges of the donor and recipient vessels to visualize the edges clearly during the anastomotic procedure. Non-traumatic microvascular clips were applied on the recipient vessel and two silicon triangle-shaped background sheets inserted beneath, in order to simplify the construction of the anastomosis. Thereafter, a linear arteriotomy on the cortical recipient vessel was performed. Two 10-0 monofilament sutures were used to anchor the donor and recipient vessel at the toe and the heel of the anastomotic site. The anastomosis was then completed by means of interrupted microsutures to allow eventual anastomosis growth with time. First the distal and then the proximal temporary clips on the cortical MCA recipient artery, and subsequently the clip on the proximal STA were removed. Verification of the bypass patency was performed by Indocyanine Green Videoangiography (performed by using a commercially available surgical microscope, OPMI® Pentero™, The Carl Zeiss Co., Oberkochen, Germany). Bidirectional flow through the MCA was assessed and all flows were quantified (18 ml/min) using a flow probe (Transonic system, Inc.© Ithaca, NY, USA). After establishing the bypass, EMS was performed. The

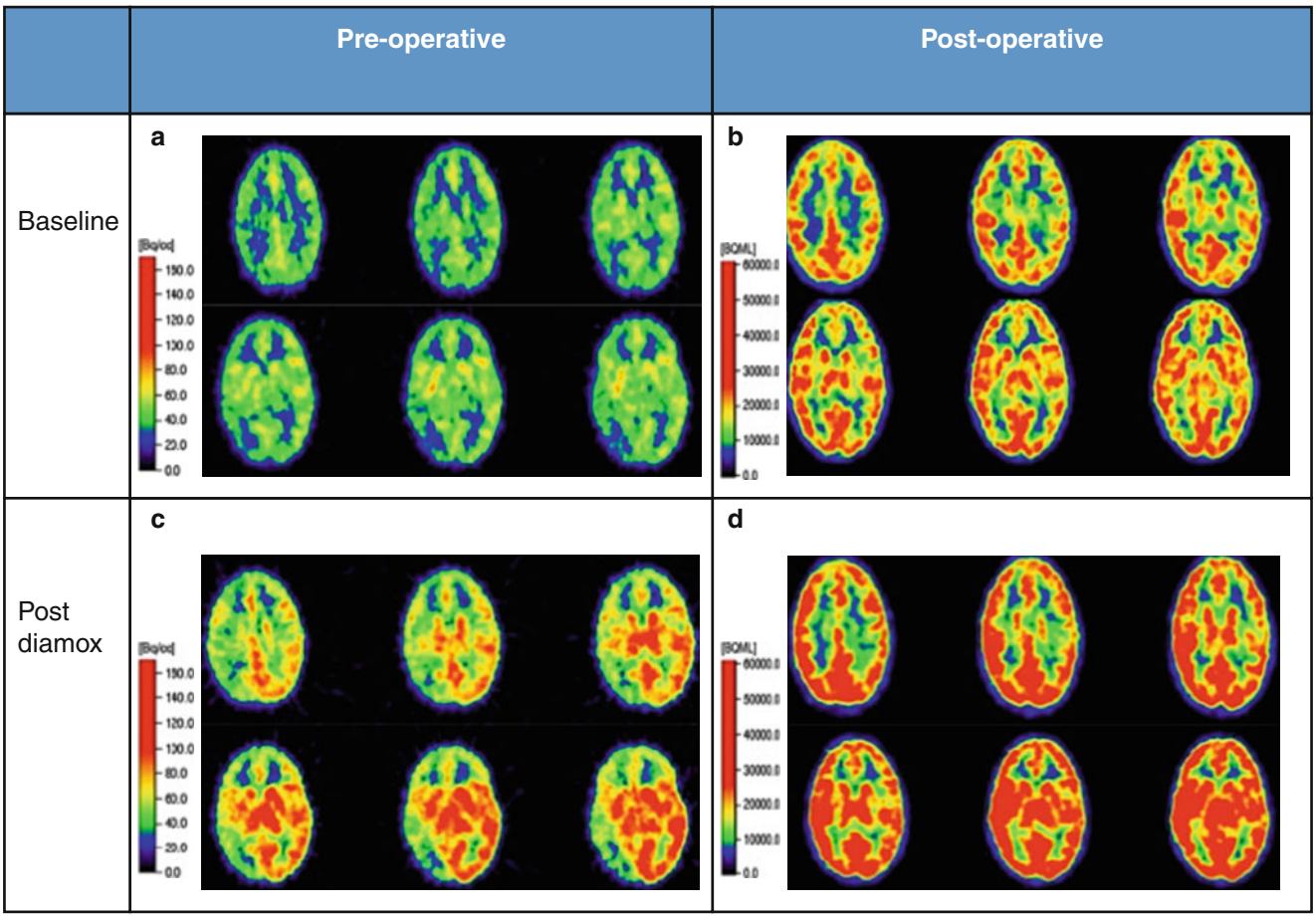

Fig. 1 (**a**, **c**) Pre-operative [^{15}O]H_2O-PET scan revealed severe baseline perfusion deficits and almost absent CVR after acetazolamide administration in almost the entire right hemisphere. Left hemispheric baseline CBF was moderately affected and CVR was largely preserved, with exception of the left frontal region. (**b**, **d**) One year and 8 months postoperatively, the [^{15}O]H_2O-PET revealed clear improvement of CVR in the right hemisphere and the left frontal regions. The non-operated left MCA territory showed decreased CVR compared to preoperatively

previously made burr hole was enlarged to permit the intracranial entrance of the bypass without risk of compression, and the bone was returned to its normal position and secured in place.

Bifrontal revascularization through EDPS was performed by extending the skin incision 4 cm over the midline in a zigzag fashion to optimize cosmetic results. The scalp flap was reflected anteriorly and a vascularized pediculated (towards the bitemporal and biorbital regions) bifrontal pericranial flap consisting of periosteum was prepared by careful dissection (Figs. 2a and 3a). After the completion of two separate frontal parasagittal craniotomies (dimensions 4×5 cm) (Figs. 2a and 3b), the dura was opened in a star-shaped fashion and a bifrontal EDS was performed by inverting the dural flaps beneath the edges of each bone window (Fig. 2a). The craniotomies were localized 2 cm away from the midline to avoid injuring the superior sagittal sinus (SSS) and the parasagittal veins. Hereafter, the bifrontal encephalo-periosteal-synangiosis (EPS) was accomplished by small arachnoidal openings with positioning of the previously prepared pediculated periosteal flap over the cortical convexity on both sides (Fig. 2b). Finally, the periosteal flap was sutured laterally to the dural edges, the two frontal bone opercula repositioned and fixed, and the scalp flap re-approximated and closed (Figs. 2c and 3c).

Results

The patient had no new neurological deficits after awakening in the pediatric intensive care unit. After hospital discharge, she only experienced three short episodes of monoparesis of the left arm (that were diagnosed as TIAs) in the first 3 months following surgery, but never had recurrent ischemic symptoms in the almost 2 years that followed.

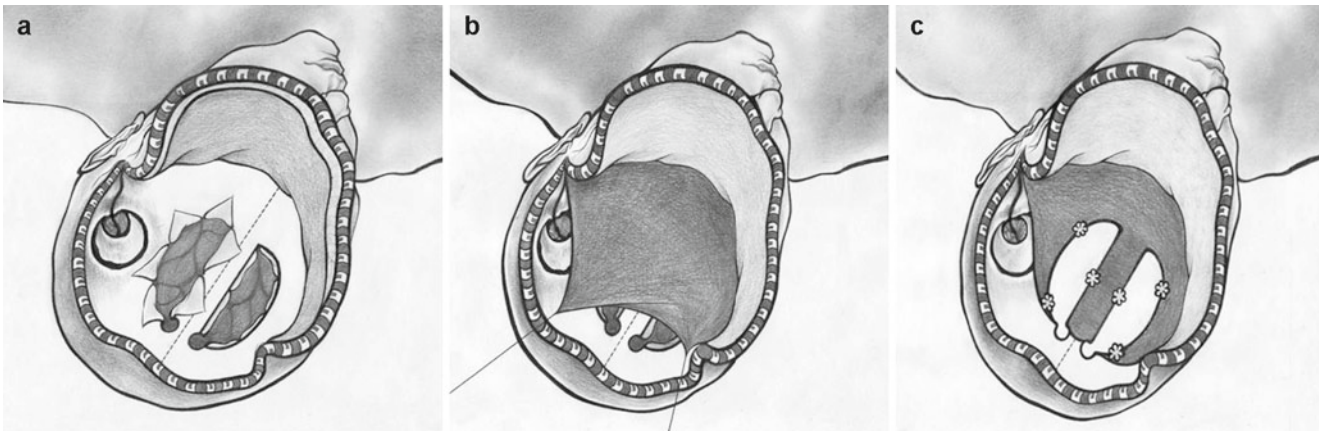

Fig. 2 Illustrations of the one-staged technique for revascularization of the left MCA and bifrontal territories. (**a**) After performing an STA-MCA bypass and EDMS, the skin incision is extended for 4 cm over the midline behind the hairline and the scalp flap is reflected anteriorly. The vascularized frontal cranial periosteum is dissected and reflected on the scalp flap, two symmetric bilateral frontal parasagittal craniotomies are performed and the underlying frontal dura is opened in a star-fashion and inverted on the cortex around each frontal bone window (EDS). (**b**) The dissected pericranial flap is placed over the cortex (EPS) and sutured to the dural edges. (**c**) Finally, the bone flaps are repositioned

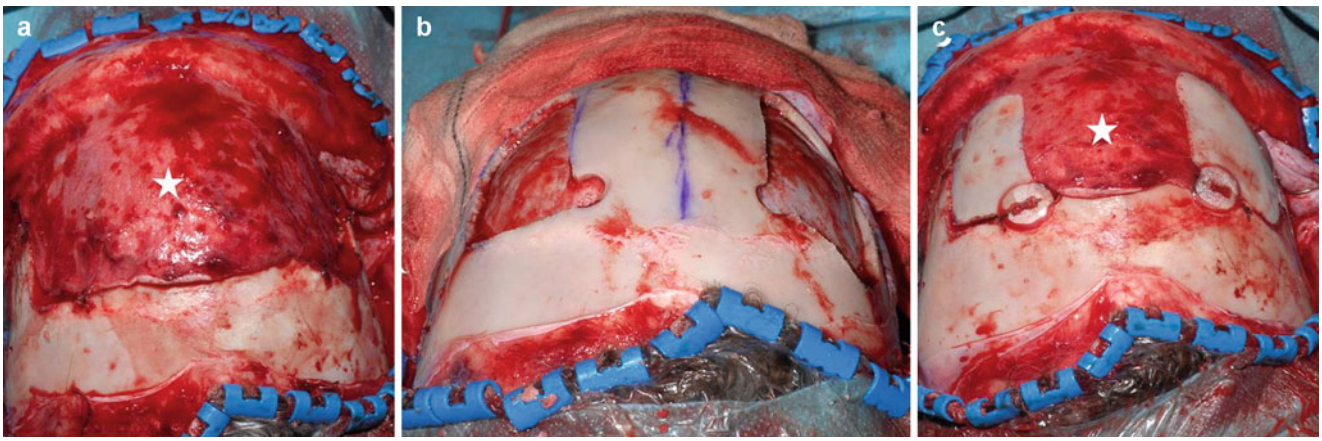

Fig. 3 Intraoperative pictures of an EDPS. (**a**) Dissection and preparation of the vascularized frontal cranial periosteum (*white asterisk*). (**b**) Bifrontal craniotomies located 2 cm from the midline (*blue drawn line*). (**c**) After dural opening in a star-fashion and dura-synangiosis, the periosteal flap (*white asterisk*) is placed over the cortex, sutured to the dural edges (EDPS). Finally, the bone flaps are repositioned

Furthermore, a good cosmetic outcome was objectified. The 1.8 year post-operative [^{15}O]H_2O-PET documented clear improvement of CBF and CVR in the right hemisphere and the left frontal regions. The non-operated left MCA territory showed decreased CVR compared to preoperatively (Fig. 1b, d).

Discussion

Next to revascularization in the MCA territory, re-establishing CBF in the anterior cerebral artery (ACA) area is most likely to be of importance [20, 23, 24]; neurocognitive development has been correlated to frontal lobe CBF [18, 24]. In this report we described a cerebral revascularization technique for pediatric patients with MMV that enables increasing CBF in three different vascular territories. The described procedure permits (1) achieving an immediate unilateral MCA flow augmentation by performing a STA-MCA bypass and reinforcing the blood supply by promoting neoangiogenesis in the MCA territory by means of EDMS, and (2) revascularizing the bifrontal territories with EDPS. This technique represents a modification of previously reported techniques for the revascularization of the frontal lobes [8, 11–13, 16, 18, 20, 23]. The novelty of this technique is unfolded in the one-stage approach, combining direct and indirect revascularization in three different areas, with minimal surgical risks (by avoiding the IF and SSS). To the best of our knowledge, this one-stage procedure has not been reported in the literature.

Revascularization with frontal pericranial flaps in patients with MMV has shown to be effective in promoting frontal synangiosis [20]. In the technical modification presented, the revascularized frontal area is further expanded by inverting and reflecting dural flaps over the cortex for each craniotomy. This bifrontal EDPS method is easy to perform and can be

applied in patients with MMV who suffer from bifrontal hypoperfusion with hemodynamic impairment. It represents a good alternative to the existing techniques for frontal territories revascularization, such as the technically challenging direct STA-ACA bypass or other procedures that need exposure of the interhemispheric fissure (IF) [10, 11, 13]. In fact, the use of separate frontal parasagittal craniotomies, located one on the left side and one on the right – 2 cm away from the midline – reduces the risk of injuries to the SSS and the parasagittal veins. With this technique, no exposure of the IF is needed. Furthermore, the procedure does not compromise eventual future contralateral MCA territory revascularization. By placing the incision behind the hairline in a zig-zag fashion with a non-shaving policy, a nice cosmetic result can be guaranteed.

In addition, bifrontal EDPS itself could be used as a supplementary procedure, even in patients who already underwent other cerebral revascularization procedures in case symptoms develop related to hypoperfusion of the bifrontal territories or in case of progression of the MMV.

This technique represents a modification of previously reported techniques for the revascularization of the frontal lobes [8, 11–13, 16, 18, 20, 23]. The novelty of this technique is unfolded in the one-stage approach, combining direct and indirect revascularization in three different areas, with minimal surgical risks (by avoiding the IF and SSS).

Conclusions

The one-stage technique for contemporary revascularization of three different vascular territories allows unilateral combined revascularization of the MCA territory by a direct STA-MCA bypass and EDMS, as well as indirect revascularization of the bifrontal territories by EDPS. This technique seems to be a safe and effective alternative treatment for patients with hemodynamic compromise in both frontal territories in addition to the MCA region. Furthermore, the EDPS itself could be used as a supplementary effective and safe revascularizing option in patients with MMV who already underwent direct or indirect bypass procedures in the MCA territory.

Conflict of Interest We declare that we have no conflict of interest.

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"How I Do It:" Non-occlusive High Flow Bypass Surgery

Albert van der Zwan

Abstract Giant intracranial aneurysms are a formidable challenge for treatment, considering their grim prognosis. Until lately, endovascular treatment options have been disappointing, and neurosurgical treatment results are by far the most promising. In the neurosurgical treatment of giant intracranial aneurysms, the non-occlusive nature of the ELANA anastomosis technique is a major advantage in flow replacement bypass surgery where large proximal arteries with higher flows need to be replaced or reconstructed. The construction of a deep intracranial anastomosis using the ELANA technique needs less vessel exposure than when using a conventional occlusive technique. This extra advantage facilitates the construction of anastomoses even on the ICA, MCA, ACA, P1, P2, SCA or BA, using the trans-Sylvian route only, without major skull base surgery. Several different types of EC-IC and IC-IC flow replacement bypass are now safely applicable due to the non-occlusive character of this technique.

Future improvements of the technique are focused on sutureless applications, graft improvements and Flow Model Simulation. It is clear that not only conventional bypass techniques, but also, and even especially, the ELANA bypass technique, are of great value in the treatment of giant aneurysms.

Keywords Bypass surgery • Cerebral revascularization • Elana • Giant aneurysms • Neurosurgery • Non-occlusive anastomosis

A. van der Zwan
Department of Neurosurgery,
Rudolf Magnus Institute of Neuroscience,
University Medical Center Utrecht,
PO Box 85500, Utrecht, 3508 GA, The Netherlands
e-mail: a.vanderzwan@umcutrecht.nl

Introduction

Although modern endovascular techniques are increasingly available for the treatment of intracranial aneurysms, today's vascular neurosurgeon is confronted with very complex and large aneurysms that are treatable using only vascular reconstructive techniques. These mostly giant intracranial aneurysms, appoximately 5 % of all intracranial aneurysms, are among the most challenging lesions in vascular neurosurgery. These aneurysms are predominantly located in those proximal parts of the vascular tree with high blood flow, such as the internal carotid artery (cavernous and supraclinoid ICA), the proximal middle cerebral artery (MCA), the proximal anterior cerebral artery (ACA), the basilar artery (BA), the pre- and postcommunicating posterior cerebral artery (P1, P2) and the superior cerebellar artery (SCA). Generally they appear during the fifth to seventh decades of life. Most of these aneurysms (20–70 %) present with rupture and they have the same re-rupture rate as other smaller aneurysms. The second most common presentation is the mass effect of these aneurysms causing ocular movement disturbances due to cranial nerve palsies, vision or vision field loss, and focal weakness/gait disorders, headache and seizures. Thirdly, approximately 8 % of giant aneurysms present with ischemic syndromes, probably due to embolic phenomena originating from the aneurysm sac into more distally located vascular territories. In general, the natural history of these aneurysms is very poor with high morbidity and mortality rates of 65–85 % within 2 years of diagnosis [1,2].

Therefore, effective treatment of these lesions is life-saving. However, this begs tremendous and intensive investment in pre-treatment diagnostics and considerations regarding the two aims that are the most important in the treatment of giant aneurysms: first is the permanent exclusion of the aneurysm from the circulation, and the second is the relief of the mass effect that in some cases also plays a role in symptomatology.

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In most giant aneurysms, direct clipping or reconstructive clipping is not possible and flow replacement bypass techniques should be applied. Besides the conventional bypass technique, the non-occlusive Excimer Laser Assisted Non-occlusive Anastomosis Technique (ELANA), as developed at our institute, provides us with an extra valuable tool for replacing higher flow arteries such as the intracranial ICA, proximal middle cerebral MCA, ACA, SCA, and BA [3]. In the strategy of replacing these major vascular arteries, the anatomy of the aneurysm plays an important role;, however, nowadays intra-operative flow measurements (Transonic Inc. ®, Ithaca, NY, USA) additionally enable us to determine more quantitatively which vessels should be replaced using the safest technique. This more tailored approach makes it possible to treat aneurysms that previously were not treatable without major risks. The ELANA technique facilitates the construction of an end-to-side anastomosis without temporary occlusion of the recipient artery with a diameter larger than 2.6 mm. Although this technique was primarily developed for cerebral augmentative revascularization, it turned out that the technique was also very feasible for creating protective or replacement bypasses [3–6].

In addition, in very complex giant aneurysms, combinations of both conventional and ELANA techniques can be applied, depending on the flows of multiple branches originating from the aneurysm.

Although the most frequently performed high flow bypass in our institution is made between the ECA extracranially and the internal carotid artery (ICA) bifurcation intracranially, the ELANA technique is also suitable for IC-IC replacement.

At the inflow side of an IC-IC bypass, we perform per definition an ELANA anastomosis, because this anastomosis is constructed on a large proximal cerebral artery (>3 mm). Therefore an important criterion for this bypass, next to a healthy-looking recipient vessel wall surface, is enough surgical space at the bypass inflow site to suture the ELANA anastomosis. Moreover, there has to be enough intracranial space for a bypass conduit. At the distal side, the character of the anastomosis depends on the size of the artery and the level of branching, with the same criteria as the outflow anastomosis of the high-flow EC-IC bypass. If an IC-IC bypass is possible, we generally prefer it over an EC-IC bypass because a large surgical exposure using the external carotid artery (ECA) is avoided. Since the introduction of the ELANA technique in 1991, we have operated on more than 350 cases, mostly for flow replacement (305 patients), but also for flow augmentation in case of ICA occlusion (55 patients).

Materials and Methods: The ELANA Anastomosis

An ELANA anastomosis can only be constructed on vessels with a minimal diameter of 2.6 mm, such as the proximal intracranial ICA, MCA, ACA, BA SCA, P1 and P2. As a bypass vessel, a vein (mostly the vena saphena magna, VSM) or radial artery (RA) can be used. The inner diameter should be a minimum of 2 mm to enable the laser catheter to pass through the donor vessel. First, depending on the size of the recipient or donor artery, a platinum ring of 2.6 or 2.8 mm is attached to the distal segment of the bypass vessel using 8 microsutures. The ring with the attached distal donor segment is subsequently stitched end-to-side to the recipient, again using 8 microsutures. This is followed by the passing of the ELANA 2.0 ® laser suction catheter down the lumen of the open donor vessel. The tip of the catheter is placed against the sidewall of the recipient vessel. After 2 min of active suctioning from the dedicated inside portion of the catheter, the laser fibers on the outside of the catheter are activated for 5 s. The laser broaches the recipient arterial wall and separates an arteriotomy flap from the recipient. The suction portion of the catheter maintains contact with the small arteriotomy flap, thus preventing its migration into the lumen of the recipient. The catheter is then withdrawn and the anastomosis is made. To prevent blood loss, a temporal clip is placed on the vein and the other side of the bypass can now be created by conventional bypass technique on the ECA, superior thyroid artery, or superficial temporal artery for EC-IC bypass purposes or other proximal intracranial arteries for IC-IC bypass creation using the ELANA technique as well.

Results

ELANA EC-IC Bypass for Giant Aneurysms of the ICA

Between 1999 and the end of 2010 we operated on 45 patients with giant aneurysms of the cavernous and supraclinoid ICA [7]. Mean age was 53 (SD 15) and predominantly female (75 %). Presentation of symptoms was exclusively cranial nerve compression signs in 27 patients (75 %) and subarachnoid hemorrhage (SAH), with or without cranial nerve compression signs in 14 patients (31 %). In the remaining 4 patients, the aneurysms were without symptoms. In all of the patients we used the VSM as a bypass vessel. The vein was cut in half and first the ELANA anastomosis was created

on the intracranial ICA, ICA bifurcation or proximal MCA. In the second phase, the other half of the vein was used to make a conventional end-to-side anastomosis on the external carotid artery, and finally both vein pieces were connected in an end-to-end anastomosis. The mean surgical time for the bypass procedures of all patients was 443 min (range, 300–750 min). During surgery, the recipient or donor artery was never occluded as part of the bypass procedure. A successful patent EC-IC bypass was constructed in 44 of 45 patients (98 %). After ligation of the ICA, a mean intra-operative bypass flow of 102 ml/min (range, 65–170 ml/min) was recorded, using a flow probe (Transonic Inc. ®, Ithaca, NY, USA). Postoperative MRA flow measurements, performed in 15 patients, revealed a mean bypass flow of 138 ml/min (range, 70–180 cc/min). Control imaging of all patients showed ICA aneurysm thrombosis.

Favorable long-term follow-up outcome (postoperative modified Rankin Scale – mRS – equal or inferior to preoperative mRS) was found in 35 patients (78 %, mean long-term follow-up: 3.3 years, 0.6–5.6 years). Defining patients with an mRS score of 3 (moderate disability, needing help in daily life, but walking without assistance) or worse as dependent, 37 patients (82 %) of our patient group were independent in the long term.

Cranial nerve recovery occurred in 42 % of the patients.

ELANA Bypass for Giant Aneurysms of the MCA

As MCA giant aneurysms are even more life-threatening lesions prone to rupture compared to giant aneurysms of the ICA, an aggressive therapeutic strategy is even more warranted [1].

In our institute we prefer to treat these aneurysms using IC-IC ELANA replacement bypass followed by trapping of the complete aneurysm after determining the flow to be replaced combining pre-operative (MRI) and intra-operative flowmetry data. Since 1999 we have treated 25 patients with giant aneurysms with a mean diameter of 38 mm (SD ± 12 mm) measured on imaging [8]. Mean age was 45 years (SD ± 16 years) and 12 patients were female (48 %). All aneurysms were assessed as being not safely clippable or coilable. In 11 patients (44 %), the aneurysm presented with SAH, in 3 patients (12 %) with ischemic stroke, in 3 patients (12 %) with epilepsy, in 3 patients with TIA (12 %) and in 4 patients no objective symptoms were found.

Three types of ELANA bypasses were performed in this group of patients, all using the VSM as bypass graft.

Type I ICe- ICe (Complete ELANA Type)

Type I is defined as an IC-IC bypass with proximal and distal anastomoses constructed, both using the ELANA technique (ICe-ICe). This type of bypass was performed in 12 patients (36 %). The proximal anastomosis was made on the proximal ICA ($n = 8$) or MCA ($n = 4$), depending on accessibility and quality of these proximal arteries. The VSM was cut in half and the anastomosis was constructed on the ICA or proximal MCA. After completion of this anastomosis, a temporal clip was placed on the vein. The distal anastomosis was mostly made on the distal MCA (M2: $n = 10$, M3: $n = 2$) using the second half of the VSM, again followed by temporally clipping this vein. The two vein halves were then anastomosed end-to-end and just before finalizing were flushed by removing both temporal clips. An example of this type of bypass is shown in Fig. 1a, b. As no temporal occlusion of any of the vessels is necessary, we prefer to construct this type of bypass.

Of special interest is a young, asymptomatic patient in whom we were in the process of finishing the final end-to-end anastomosis when the aneurysm spontaneously ruptured, so for the last few minutes the MCA had to be temporally clipped to finish the bypass. At that moment there was no reflux at all coming from the distal MCA, showing that the leptomeningeal collaterals were minimally potent. This finding again stresses that temporal occlusion of the proximal MCA for conventional anastomosing techniques should be avoided in all cases. The few minutes of the temporal occlusion of the MCA in this patient resulted in a temporal paresis, fortunately lasting only a few weeks.

In three patients, the configuration of the aneurysm was very complex with an extra MCA branch originating from the aneurysm. Therefore an extra EC-IC bypass was constructed considering the size of these smaller branches, using conventional anastomosing techniques (end-to-side STA-distal MCA).

Type II. ICe-ICc (Proximal ELANA-Distal Conventional Type)

Type II is defined as an IC-IC bypass with an ELANA anastomosis on the proximal side and a conventional anastomosis on the distal side, as the distal MCA branch is not always large enough (>2.6 mm) to construct an ELANA anastomosis on ICe-ICc. This type was constructed in 14 patients (56 %). The proximal ELANA anastomosis was made on the ICA ($n = 10$) and on the proximal MCA ($n = 4$). Distal conventional anastomoses were made on the M2 ($n = 4$) and on the M3 ($n = 10$).

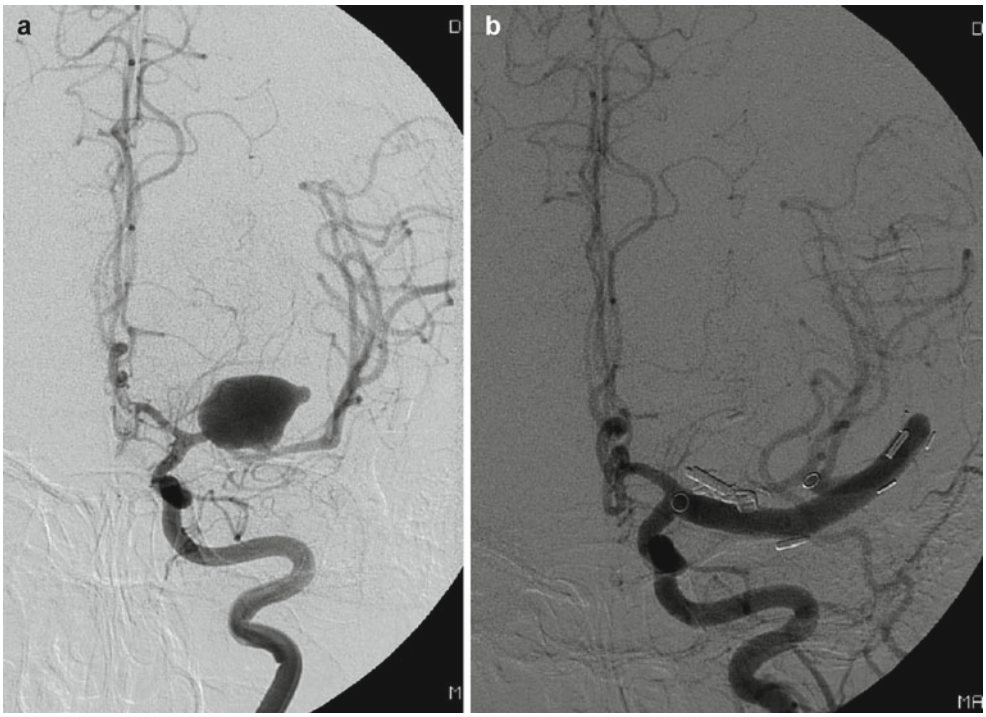

Fig. 1 (**a**) Pre-operative angiogram of a symptomatic giant aneurysm of the left MCA. (**b**) Post-operative angiogram of patient of (**a**) after creation of an IC-IC bypass (Type I: ICe-ICe: Complete ELANA type) and trapment of the MCA including the aneurysm

Type III. EC-Ice (Proximal Extracranial Conventional – Distal ELANA Type)

This type is defined as an extracranial-to-intracranial bypass with an ELANA anastomosis on the distal side (EC-ICe). In two patients (8 %), the intracranial ICA or MCA proximal to the aneurysm was not surgically reachable due to aneurysm size. Therefore an EC-IC bypass with a distal ELANA anastomosis on the distal MCA and a proximal anastomosis on the ECA was constructed. This type of flow replacement bypass was described previously in the treatment of internal carotid aneurysms.

All 40 ELANA attempts resulted in a patent anastomosis with a strong backflow directly after ELANA catheter retraction. In six ELANA anastomoses (15 %), the disc of the arterial wall, which is normally attached to the tip of the catheter after laser application and catheter retraction (the flap), was not found on the tip. In these patients, no adverse events occurred and bypasses were functioning well.

Mean intra-operative flow ± SD through the 23 IC-IC bypasses before any part of the MCA or aneurysm was occluded was 15 ± 10 cc/min. The mean intra-operative flow ± SD through the IC-IC bypasses after partial or full MCA occlusion, measured at the end of the operation, was 53 ± 13 ml/min. The two EC-IC bypasses had a flow before MCA occlusion of 35 and 50 ml/min, respectively. These aneurysms were treated endovascularly the next day and MR flow measurement on the first EC-IC bypass showed that bypass flow had increased from 35 cc/min (intra-operatively) to 100 cc/min postoperatively end after endovascular occlusion of the parent artery. However, nowadays we prefer to treat these aneurysms intra-operatively directly after the bypass construction by ligating the ICA.

In long-term follow-up (mean, 3.6 years; range, 0.2–7.7 years after surgery), 20 patients (80 %) had a favorable outcome, meaning that their postoperative mRS score was equal to or higher than their preoperative status. Five patients (20 %) had a long-term unfavorable outcome. In four of these patients, the unfavorable outcome was related to surgery (16 %). One patient (5 %) died 2 months after surgery from an unknown cause, although the patency of the bypass and the trapping of the aneurysm of this patient was angiographically confirmed 2 weeks before death.

Defining patients with an mRS score of 3 (moderate disability, needing help in daily life, but walking without assistance) or worse as dependent, long-term independency, amounted to 16 patients (64 %).

ELANA Bypass for Giant Aneurysm of the ACA

Although we frequently see patients with giant aneurysms of the ACA, it is rarely necessary to use the ELANA technique for bypassing these lesions. An example of this was a 61-year-old patient with an SAH and a giant aneurysm of the ACA that was not coilable, and because of multi-calcifications not easy clippable. We performed an IC-IC bypass from the A1 (ELANA) to the proximal A2 (conventional), as the STA in this case was very small.

Intra-operative flow measurements on the A2 showed a flow of 30 cc/min to be replaced. After the bypass was finished, the aneurysm, including the distal A1 and anterior communicating artery, was trapped. According to intra-operative flow measurements, initial flow in the bypass with the A1 still open was 15 cc/min but went up to 30 after trapping the aneurysm, including the A1-A2 segment, demonstrating that the bypass functioned as a 100 % replacement bypass. The patient recovered very well and is back to work (follow-up at 40 months), and CTA control after 2 years showed the bypass to be fully patent.

ELANA Bypass for Giant Aneurysms of the Posterior Circulation

Giant aneurysms of the posterior circulation are even more challenging than those of the anterior circulation. The major reasons are most often the large size of the aneurysm and the little space that is left for the thrombosing and consequently swelling aneurysm. In addition, thrombosing perforators coming out of the aneurysm often cause devastating infarcts in the brainstem with consequent sequelae. Finally, complete trapping is seldom possible, leaving the risk of bleeding of the aneurysm.

We treated 10 patients with giant aneurysm of the posterior circulation with an ELANA bypass on the BA, the P1, P2 or the SCA [9–11]. Of the group of 10 patients, only 2 had a good functional outcome (20 %). The remaining 8 patients suffered from progressive brainstem ischemia or rupture of the solely proximally occluded aneurysm. Therefore, although it is quite possible to create an ELANA anastomosis on the posterior circulation, the thrombosis of the aneurysm and consequent occlusion of the perforators make the prognosis of treatment of these giant aneurysms slim.

Discussion

The major advantage of the ELANA procedure is its non-occlusive character. Secondly, for creating this non-occlusive type of anastomosis, less intracranial arterial exposure is needed, as temporal clips are not needed. Thirdly, no brain protective measures – such as hypothermia – are needed, as the complete procedure is non-ischemic. Fourthly, as there is no blood exposure to the ring and maximally four through-the-vessel-microsutures are needed, adequate re-endothelialization is achieved [12]. Therefore, safe anastomoses can be made on proximal intracranial arteries such as the ICA, MCA, ACA, P1,SCA and BA. In our institute, more than 300 patients and worldwide a large cohort of more than 400 patients have been treated using the ELANA technique between 1992 and 2011 with good results and good long-term patency rates (up to 93 %).

Although the ELANA technique prevents ischemic risk for the brain and vessel wall manipulations associated with temporary occlusion, the technique is still surgically challenging. For future improvements of the procedure itself, we are currently in the process of developing a simpler variant without microsutures in our research laboratory to further reduce brain and artery manipulation. In addition, optimizing the quality of interposition grafts, even combined with artificial cellular matrixes, bio-engineering of vessels from stem cells or the use of donor cadaver vessels, could improve the present patency rate of 93 %. Finally, Model Flow Simulation using flow parameters of the Circle of Willis preoperatively measured can be helpful in determining the amount of blood flow that has to be replaced and consequently in tailoring the treatment of these difficult-to-treat aneurysms.

Conflict of Interest We declare that we have no conflict of interest.

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The Role of MCA-STA Bypass Surgery After COSS and JET: The European Point of View

Daniel Hänggi, Hans-Jakob Steiger, and Peter Vajkoczy

Abstract The results of the previously published Carotid Occlusion Surgery Study (COSS) and the Japanese EC-IC Bypass Trial (JET) seem to influence the position towards surgical treatment for ischemic cerebrovascular disease (Ogasawara and Ogawa, Nihon Rinsho 64(Suppl 7):524–527, 2006; Powers et al., JAMA 306:1983–1992, 2011).

The goal of this article is to give the European point of view after COSS and JET on behalf of the Cerebrovascular Section of the European Association of Neurological Surgeons (EANS).

Keywords EC-IC bypass • STA-MCA bypass • Cerebral revascularization • COSS • JET • EANS

Historically, the EC-IC Bypass Trial published in the 1980s failed to demonstrate a benefit of superficial temporal artery to middle cerebral artery bypass in more than 1,300 patients suffering from symptomatic internal carotid artery or middle cerebral artery atherosclerotic disease [1]. In the following years, the study was widely criticized, predominantly due to (1) the large number of patients operated on at participating centers who were not included in the study (selection bias), and (2) the lack of patient selection based on hemodynamic assessment [2, 6]. Subsequently, in the 1990s the analysis of hemodynamic impairment to predict the risk of stroke became more important and it was recommended to identify candidates for bypass surgery according to hemodynamic criteria.

In JET, in a prospective randomized setting, the inclusion criteria were (1) transient ischemic attacks (TIA) or ischemic stroke in the territory of an occluded carotid artery, and (2) resting-cerebral blood flow (CBF) < 80 % and increase of CBF <10 % after Diamox® as demonstrated by Single-Photon Emission Computed Tomography (SPECT), PET (Positron Emission Tomography) or Xenon Computed Tomography (Xe-CT) [4]. Furthermore, the patients were divided into two risk groups (moderate versus severe ischemia) according to the Diamox® challenge test. Over a study period of almost 4 years and a 2-year follow-up, 196 patients were included in JET. The results showed a significant reduction of the primary (complete stroke or death) and secondary (recurrent ipsilateral ischemia) in the surgically treated patients. Furthermore, the overall perioperative morbidity was calculated to be <5 %. As the major limitation, it has to be mentioned that results of JET so far have not been published in a peer review journal.

In COSS, the main inclusion criteria were (1) transient ischemic attacks (TIA) or ischemic stroke in the area of an occluded carotid artery, and (2) ipsilateral-to- contralateral hemispheric mean Oxygen Extraction Fraction (OEF) ratios >1.13. A sample-size power calculation was based on the STLCOS data and it was estimated to require a total of 372 patients. The primary outcome was defined as all stroke and death within 30 days after surgery and ipsilateral ischemic stroke within 2 years [5]. Based on an interim analysis, the study was preliminarily halted after the inclusion of 195 patients due to the following observations:

1. The 30-day event rate in the surgical group was about 14.4 %.
2. The 2-year outcome rate did not differ significantly between the surgical (21 %) and medical groups (22.7 %).

An explanation about COSS, on behalf of the Cerebrovascular Section of the European Association of Neurological Surgeons (EANS), has been published elsewhere [3].

In conclusion, and based on the present data of COSS and JET, the EC-IC bypass remains an option in carefully selected patients after ischemic cerebrovascular disease, limited to interdisciplinary and specialized high-volume

D. Hänggi, MD (✉) • H.-J. Steiger, MD
Department of Neurosurgery, Heinrich-Heine-University, Moorenstraße 5, Düsseldorf 40225, Germany
e-mail: daniel.haenggi@uni-duesseldorf.de

P. Vajkoczy
Department of Neurosurgery, Charité Universitaetsmedizin, Berlin, Germany

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centers and within the framework of controlled studies. Ultimately, the present data underscores the fact that EC-IC bypass surgery, performed at dedicated centers with a perioperative stroke rate lower than 7–10 %, might be beneficial after ischemic cerebrovascular disease.

Conflict of Interest We declare that we have no conflict of interest.

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STA-MCA/STA-PCA Bypass Using Short Interposition Vein Graft

Yasuhiko Kaku, Naoko Funatsu, Masanori Tsujimoto, Kentarou Yamashita, and Jouji Kokuzawa

Abstract *Background and aims*: Superficial temporal artery (STA) is the mainstay of donor vessels for extra-intracranial bypass (EC-IC bypass) in cerebral revascularization. However, the typically used STA frontal or parietal branch is not always adequate in its flow-carrying capacity. In the present study, we provide an update on an alternative strategy: the use of the STA main trunk as a donor vessel, with a short vein interposition graft.

Methods: Seven patients in whom the STA main trunk was used as a donor site for anastomosis of a short interposition vein graft were included. The grafts were implanted into the M2 of the middle cerebral artery for adjunctive treatment of IC anterior wall blood-blister aneurysms in two patients, for revascularization of an internal carotid artery occlusion in one patient, into the P2/3 of the posterior cerebral artery (PCA) for adjunct treatment of complex PCA aneurysms in three patients and into the P3 of PCA for adjunct treatment of basilar artery (BA) trunk giant aneurysm in one patient.

Results: All the bypasses were patent. Intraoperative flow measurements confirmed a moderate flow-carrying capacity of the STA main trunk-interposition short vein graft (20–50 ml; mean 43 ml/min).

Conclusion: The STA main trunk has a larger diameter than the distal branch; therefore, it would be expected to have a significantly higher flow capacity than its branches. STA main trunk to proximal MCA/PCA bypass using short interposition vein grafts can provide sufficient blood flow, and may be a reasonable alternative to ECA to MCA/PCA bypass using long vein grafts.

Y. Kaku, MD (✉) • N. Funatsu, MD • M. Tsujimoto, MD
K. Yamashita, MD • J. Kokuzawa, MD
Department of Neurosurgery, Asahi University Murakami Memorial Hospital, Hashimoto-cho 3-23, Gifu, 500-8523, Japan
e-mail: kaku@murakami.asahi-u.ac.jp

Keywords STA-MCA bypass • STA-PCA bypass • Short vein graft • Moderate flow bypass

Introduction

Superficial temporal artery to middle cerebral artery (STA-MCA) bypass is an established cerebral revascularization procedure that is used in the treatment of selected cases of cerebrovascular occlusive disease, moyamoya disease, cerebral aneurysms and skull base tumors [8]. Superficial temporal artery (STA) is the mainstay of donor vessels for extracranial-intracranial bypass (EC-IC bypass) in cerebral revascularization. However, the typically used STA anterior or posterior branch is not always adequate in its flow-carrying capacity. On the other hand, typical high flow bypass between the cervical carotid artery and the intracranial vessels also has several disadvantages, including problems resulting from long grafts, hyperperfusion, and the need for additional neck incisions. In this report, the authors describe the use of the STA main trunk as an alternative donor vessel and they highlight the benefits and pitfalls of this revascularization option.

Case Materials and Methods

The authors reviewed the cases of seven patients in whom the STA trunk was used as a donor site for anastomosis of a short interposition vein graft. The grafts were implanted into the M2 of the middle cerebral artery (MCA) for adjunctive treatment of IC anterior wall blood-blister aneurysms in two patients, M3 of the MCA for revascularization of an internal carotid artery occlusion with no useable STA distal branch in one patient, the P2 of the posterior cerebral artery (PCA) for adjunctive treatment of complex PCA aneurysms in three patients, and P3 of the PCA for adjunctive treatment of a BA trunk giant aneurysm in one patient. The patient characteristics are presented in Table 1.

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Table 1 Patients' characteristics

Case	Age	Sex	Diagnosis	Recipient	Graft cut flow (ml/min)
1	44	F	R IC blood blister aneurysm	MCA (M2)	50
2	53	F	L IC blood blister aneurysm	MCA (M2)	20
3	68	F	R IC occlusion	MCA (M3)	30
4	65	M	BA trunk giant aneurysm	PCA (P3)	40
5	46	M	R PCA (P1) aneurysm	PCA (P2)	100
6	30	M	L PCA (P1/2) large aneurysm	PCA (P2)	30
7	77	M	L PCA (P1/2) giant aneurysm	PCA (P2)	30

IC internal carotid artery, *MCA* middle cerebral artery, *PCA* posterior cerebral artery

Operative Technique

The surgical technique used was as follows: An STA main trunk was dissected in the length of 2 cm, and a 10–15 cm saphenous vein was harvested from the medial ankle of the lower thigh. A fronto-temporal craniotomy was made for the approach to the recipient artery and lesion. The recipient artery (M2 of the MCA or P2/3 of the PCA) was exposed through a trans-Sylvian approach. End-to-end anastomosis between the STA main trunk and the vein graft was made using interrupted sutures with 9-0 nylon sutures. A discrepancy in the size between the vein graft (generally 2–2.5 mm in diameter) and the STA main trunk (1.5–2 mm in diameter) can be compensated for using beveled end-to-end anastomosis with a fish-mouthed cut of the STA main trunk. The cut flow of the graft was measured. The end-to-side anastomosis between the short interposition vein graft (Ca 10 cm to the MCA and 15 cm to the PCA) and the intracranial recipient artery was then performed using interrupted sutures or running sutures with 10-0 nylon sutures. After confirming the patency of the bypass, an approach to the lesion was undertaken.

Results

Successful bypass surgery using short interposition vein grafts was therefore achieved. In six of seven patients, the perioperative course was uneventful. One patient with a ruptured right PCA (P1) aneurysm died of initial damage from a severe subarachnoid hemorrhage. All of the bypasses were patent. Intraoperative flow measurements confirmed a moderate flow-carrying capacity of the STA main trunk-interposition short vein grafts (20–100 ml; mean 43 ml/min).

Illustrative Case

Case 2: A 53-year-old female patient presented with a WFNS grade 3 subarachnoid hemorrhage. CT demonstrated a diffuse subarachnoid hemorrhage and 3D CT angiography demonstrated a so-called blood blister-like aneurysm of the left internal carotid artery (Fig. 1). An STA main trunk to the left M2 bypass using interposition short vein graft was undertaken (Fig. 2a, b), and the aneurysm was treated using a wrap and clip technique (Fig. 2b). Intraoperative flow measurements of the cut flow of the bypass graft confirmed a rate of 30 ml/min. The patient tolerated the operation well. Figure 3 demonstrates the operative scar on the left medial ankle of the lower thigh from which the saphenous vein was harvested. Post-operative 3D CTA demonstrated good patency of the bypass graft (Fig. 4). The patient's post-operative course was uneventful, and the outcome was scaled as a good recovery according to the Glasgow Outcome Score.

Discussion

STA-MCA bypass was first applied in the treatment of occlusive cerebrovascular disease in 1967 by M.G. Yasargil [8]. This surgical technique has remained an important tool in the neurosurgeons' armamentarium for the management of occlusive cerebrovascular disease, moyamoya disease,

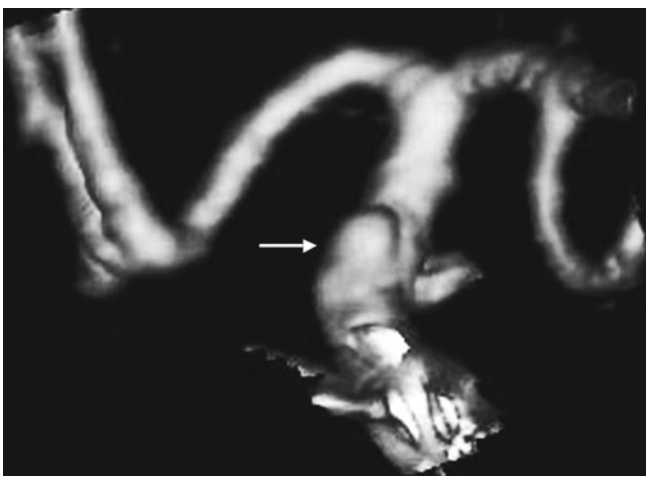

Fig. 1 3D CT angiography demonstrated a so-called IC blood blister-like aneurysm (*arrow*) in the left internal carotid artery

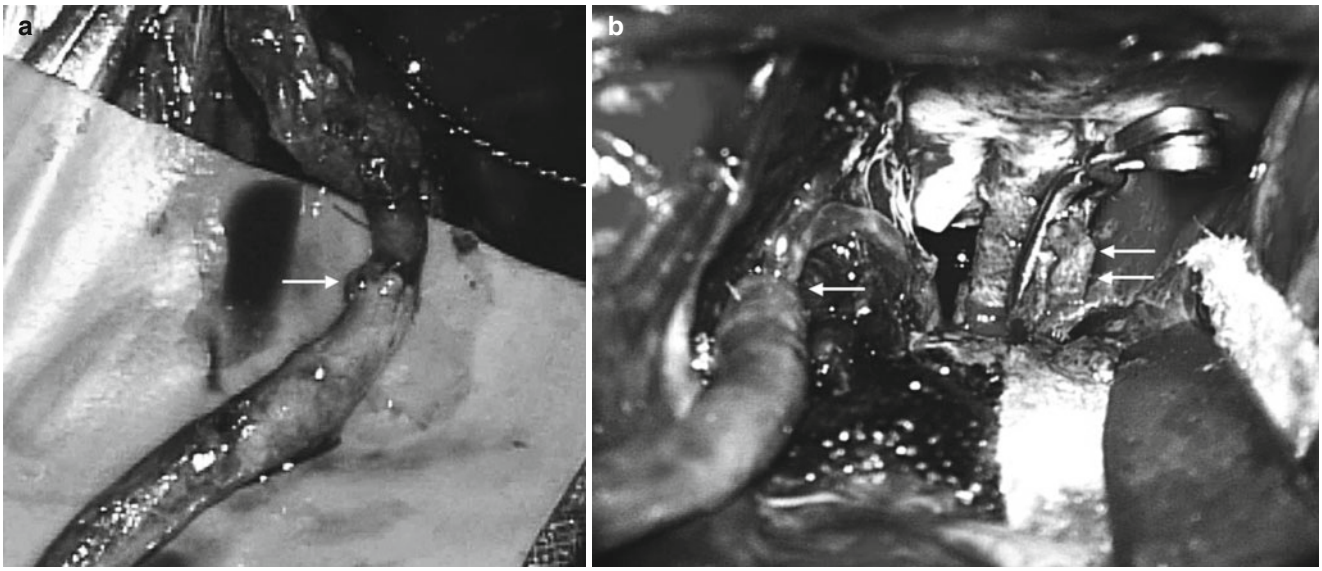

Fig. 2 (**a**) End-to-end anastomosis between the STA main trunk and a short interposition vein graft (*arrow*). (**b**) An intra-operative photograph demonstrating the STA main trunk to the left M2 bypass using an interposition short vein graft (*arrow*). The aneurysm was treated using a wrap and clip technique (*double arrow*)

cerebral aneurysms and skull base tumors. There is a demonstrable reversal of misery perfusion and marked improvement in the regional cerebral blood flow (rCBF) and cerebral metabolism in the subpopulation of patients with hemodynamic impairment who have undergone STA-MCA bypass. Recently, the use of less invasive STA-MCA bypass techniques for the surgical treatment of cerebrovascular occlusive disease has been gaining favor [3, 4]. However, the typically used STA anterior or posterior branch is not always adequate in its flow-carrying capacity at the time of aneurysm trapping. On the other hand, typical high flow bypass between the cervical carotid artery and the intracranial vessel also has several disadvantages, including problems resulting from long grafts, hyperperfusion and the need for additional neck incisions.

The STA main trunk is a valuable donor option for cerebral revascularization [1, 2, 5–7]. The STA main trunk has a larger diameter than the distal branch; therefore, the STA trunk is expected to have a significantly higher flow capacity than its branches. The STA main trunk provides a moderate and adequate flow. Intraoperative cut flow measurements demonstrated a rate of 30–70 ml/min. The use of the STA trunk allows for the use of short interposition grafts (less than 15 cm in length) rather than vein or arterial grafts from the cervical region. It is well accepted that shorter interposition grafts are desirable for graft longevity and patency. According to Poiseuille's law; $Q = \pi r^4 P / 8\eta L$ (r = internal radius, P = pressure at the vessel, η = blood viscosity, L = total length of the vessel), the radius of the vessel and the length of the graft have an impact on the blood flow. Because the flow is related to the radius raised to the fourth power, a minimal change in the radius of a vessel will have an exponential impact on the rate of blood flow. Additionally, the length of the vessel will inversely impact the blood flow. A larger graft diameter and a shorter graft length provide more blood flow. In addition, the procedure can be undertaken in a single operative field without creating an additional neck incision. Proximal STA to proximal PCA/M2 bypass using short interposition vein grafts can provide a sufficient blood flow and may be a reasonable alternative to ECA to PCA/M2 bypass using long vein grafts or STA distal branch to PCA/M2 bypass.

Conclusion

The advantages of proximal STA to proximal PCA/M2 bypass using short interposition vein grafts are as follows: (1) it provides sufficient blood flow, as the mean caliber of the proximal STA is approximately or larger than 2 mm; (2) it may have a higher patency rate, as short vein grafts are used; and (3) the use of the STA trunk can avoid the need for additional neck incisions and dissection and it also reduces the size of the incision for harvesting the interposition graft. The use of the STA main trunk with a short interposition vein graft is adequate for replacing the flow at the time of aneurysm trapping.

Conflict of Interest We declare that we have no conflict of interest.

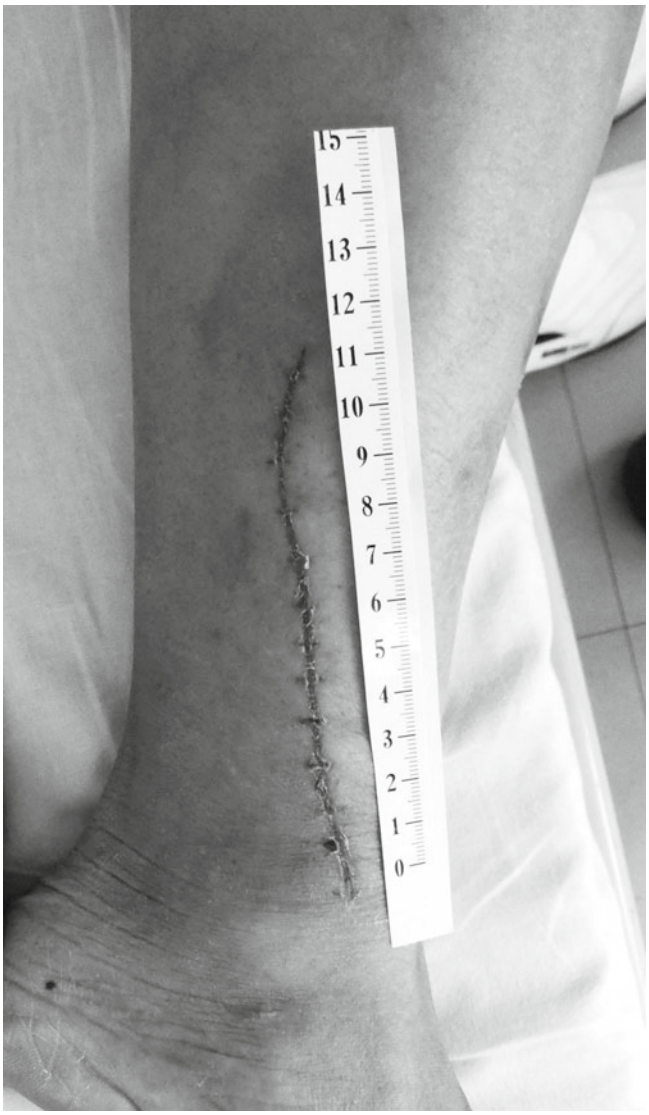

Fig. 3 A post-operative photograph demonstrating the operative scar on the left medial ankle of the lower thigh from which the saphenous vein was harvested

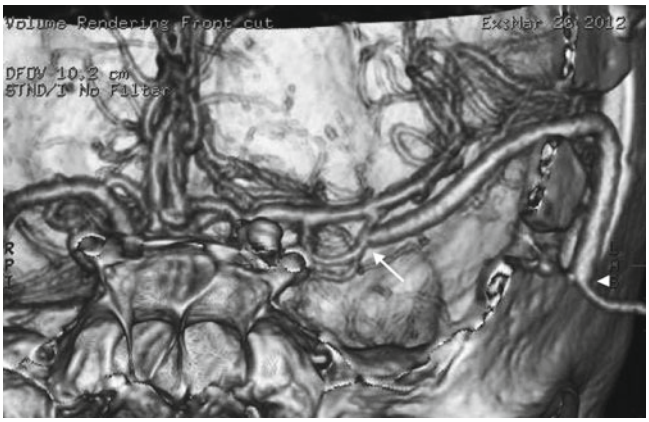

Fig. 4 Post-operative 3D CTA demonstrated good patency of the graft. The *arrow* indicates the anastomosis between the left M2 of the MCA and the vein graft, and the *arrowhead* indicates the anastomosis between the vein graft and the STA main trunk

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Endovascular Treatment for Intracranial Vertebrobasilar Artery Stenosis

Taketo Hatano and Tetsuya Tsukahara

Abstract *Purpose*: We describe our experience with endovascular treatment for symptomatic intracranial vertebrobasilar artery stenosis.

Materials and Methods: Forty-four patients with intracranial vertebrobasilar artery stenosis (37 vertebral arteries, 7 basilar arteries) were treated with endovascular surgery. Indication criteria for the treatment were (1) medically refractory symptomatic patients; (2) angiographic stenosis of more than 60 %; and (3) short lesion (<15 mm). Under local anesthesia, balloon angioplasty was first performed in all patients. Stenting was performed only in cases with insufficient dilatation, dissection, or restenosis after balloon angioplasty. The degree of stenosis, which was 83 % before treatment, was reduced to 23 % after treatment. The rate of stroke and death within 30 days was 2.3 %. Nine patients (20.5 %) developed restenosis within 6 months. Of these, four patients were symptomatic. All symptomatic patients with restenosis were successfully treated with balloon angioplasty or stenting.

Conclusion: Endovascular treatment for vertebrobasilar artery stenoses is feasible and safe in selected patients. Restenosis may be an important cause of recurrent stroke. Therefore, close clinical and neuroradiological follow-ups are essential for patients treated with endovascular surgery to improve long-term results.

Keywords Intracranial vertebrobasilar artery stenosis • Balloon angioplasty • Stent

T. Hatano, MD (✉)
Department of Neurosurgery, Fukui Red Cross Hospital,
4-1, 2 Tsukimi, Fukui-shi, Fukui 918-8501, Japan
e-mail: tahatano@kuhp.kyoto-u.ac.jp

T. Tsukahara, MD
Department of Neurosurgery, National Hospital Organization,
Kyoto Medical Center, 1-1 Mukaihata-cho, Fukakusa, Fushimi-ku,
Kyoto-shi, Kyoto 612-8555, Japan

Introduction

Intracranial arterial stenosis (IAS) is known as a major cause of stroke, especially in Asians, and is associated with a high risk of recurrent stroke [3]. The high rate of stroke in medically treated patients with IAS indicates that alternative therapies are needed for these patients.

Endovascular treatment for IAS, including balloon angioplasty and stenting, may be a promising method; however, the Stenting and Aggressive Medical Management for Preventing Recurrent Stroke in Intracranial Stenosis (SAMMPRIS) trial showed the superiority of aggressive medical management to endovascular treatment with the use of the Wingspan stent (self-expanding stent) system [9]. We report our experience of balloon angioplasty with or without stenting with a balloon-expanding stent for symptomatic stenosis of the intracranial vertebrobasilar arteries.

Materials and Methods

Between November 1998 and September 2007, 44 patients with atherosclerotic stenosis of the intracranial vaetebrobasilar artery were treated with endovascular surgery. The lesions involved the basilar arteries in 7 patients, and the intracranial vertebral arteries in 37 patients. These patients included 39 males and 5 females, with a mean age of 68.3 years (range, 46–83 years). The indication of endovascular treatment was medically refractory symptomatic patients with over 60 % angiographic stenosis. The degree of stenosis was measured using the Warfarin-Aspirin Symptomatic Intracranial Disease (WASID) trial method [12]. Only the lesions judged to be accessible with a coronary balloon-expandable stent by inspection in the pre-operation were included. Lesions longer than 15 mm were excluded.

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Procedure

Dual antiplatelet therapy was performed for at least 1 week before and 3 months after treatment. The endovascular technique was performed from a transfemoral approach under local anesthesia. After the placement of femoral artery access sheaths (6 F-25 or 5 F-90 cm), heparin was administered. During the procedure, the patient's activated clotting time was adjusted to greater than 250 s. A guiding catheter (90–100 cm in length, 6 F in diameter) or an ultra-long sheath (90 cm in length, 5 F in diameter) with a coaxial catheter (125 cm in length, 4 F or 5 F in diameter) and a guide-wire was guided to the extracranial vertebral artery. A guiding catheter or ultra-long sheath was finally advanced up to the level of the second cervical vertebra. Using a load-mapping technique, a 0.014-in. wire was advanced within the balloon catheter. The tip of the guide-wire was positioned in the second portion of one of the posterior cerebral arteries after crossing the lesion. Balloon angioplasty was first performed in all patients. The lesion was dilated slowly with a slightly undersized balloon of 10–20 % (Gateway 2.0–3.0×9–15 mm balloon; Boston Scientific) at 3–12 atm. Stenting was performed only in cases with insufficient dilatation in which residual stenosis was greater than 30 %, dissection, or restenosis after balloon angioplasty. The stents we used were balloon-expandable coronary stents (Driver, S660, S670; Medtronic); they were expanded to a diameter slightly smaller (10–20 %) than the diameter of the lumen of the normal distal artery. The pressure of the balloon inflation (6–15 atm) was decided according to the undersized target diameter of the vessels. Technical success was defined as less than 30 % residual stenosis without dissection after all procedures. Heparin was naturally neutralized and Argatroban (60 mg/day) was administered for 2 days.

Angiographic follow-up was performed 1, 3, and 6 months after endovascular treatment. Restenosis was defined as greater than 50 % stenosis.

Results

The initial presenting symptoms were transient ischemic attack (TIA) in 8 patients and stroke in 36 patients. The technical success rate was 100 %. Twenty-nine patients were successfully treated with balloon angioplasty only. Stenting was added in 15 patients. The degree of stenosis, which was 83 % before treatment, was reduced to 23 % after treatment. The mean stenosis rate was reduced from 82 to 26 % in patients treated only with balloon angioplasty and from 86 to 16 % in patients treated with stents. Periprocedural complications occurred in two patients (cerebellar infarction with transient symptoms and renal failure). The rate of stroke and death within 30 days was 2.3 %. Nine patients (20.5 %) developed restenosis within 6 months, 7 patients (24.1 %) after balloon angioplasty, and 2 patients (13.3 %) after stenting. Of these, 4 patients were symptomatic with high-grade restenosis (>70 %). All symptomatic patients with restenosis were successfully treated with balloon angioplasty or stenting. All patients received clinical follow-up for an average of 49 months (range, 8 months–7 years). Four patients developed transient episodes of VBI due to restenosis within 6 months of treatment. One of these patients developed in-stent occlusion 8 months after the initial treatment with a stent and 2 months after successful balloon angioplasty for restenosis. This patient suffered a major stroke. He stopped antiplatelet therapy by himself after the second treatment.

Representative Case

A 65-year-old male with a history of left cerebellar infarction due to left vertebral artery occlusion and hypertension presented with drop attacks and the deterioration of gait disturbance. MRI imaging revealed infarction of the left cerebellar hemisphere. Angiography revealed left vertebral artery occlusion and right vertebral artery stenosis (Fig. 1a, b). There was no collateral flow from the anterior to posterior circulation (Fig. 1c, d). Endovascular treatment was performed 1 month after onset. A 6 F guiding catheter was positioned at the left vertebral artery. The lesion was crossed with a 0.014-in. wire. Balloon angioplasty was performed with an undersized balloon (2.5×9 mm). Angiography just after balloon angioplasty showed residual stenosis of 40 %. Therefore, stenting was performed using a coronary stent with a nominal diameter of 2.5 mm and a length of 9 mm. The stent-deployment balloon was inflated to a pressure of 10 atm (unconstrained diameter of 2.5 mm). After stenting, the lesion was sufficiently dilated without complications (Fig. 1e). MRI DWI imaging after stenting revealed no fresh infarction (Fig. 2). Single photon emission computed tomography (SPECT) before and after treatment revealed improvement of the cerebral blood flow of the right cerebellum, brain stem, and bilateral occipital lobes (Fig. 3a, b). His gait disturbance improved and drop attacks disappeared after treatment. Follow-up angiography 6 months after stenting revealed no restenosis.

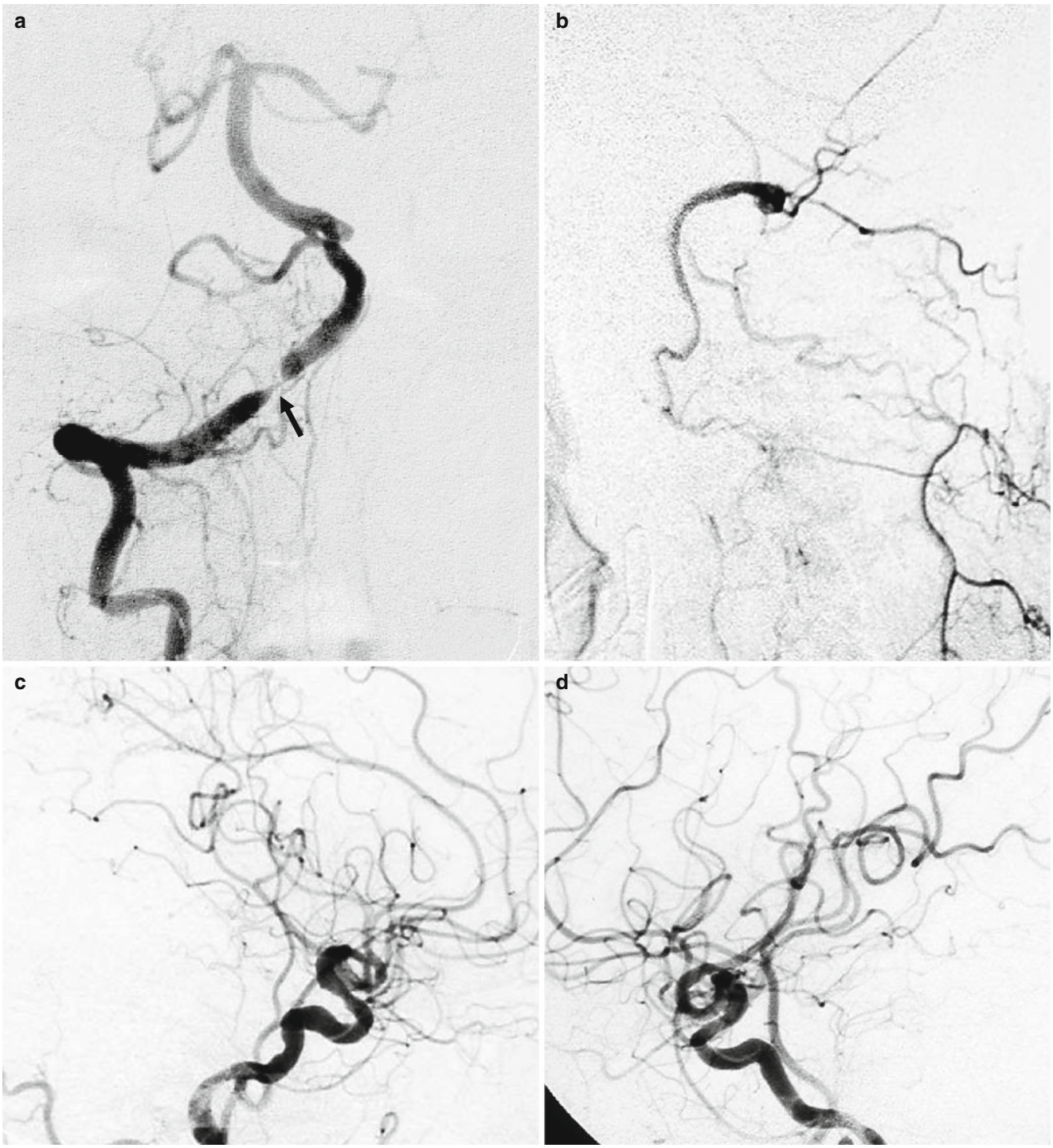

Fig. 1 (**a**) Anteroposterior view of a right vertebral artery angiogram demonstrating high-grade stenosis (*arrow*) of a right vertebral artery. (**b**) Lateral view of a left vertebral artery angiogram before treatment, demonstrating occlusion of a left vertebral artery. (**c**) Lateral view of a right internal carotid artery angiogram. Right posterior communicating artery was not revealed. (**d**) Lateral view of a left common carotid artery angiogram. Left posterior communicating artery was not revealed. (**e**) Anteroposterior view of a right vertebral artery angiogram demonstrating sufficient dilatation of the lesion (*arrow*)

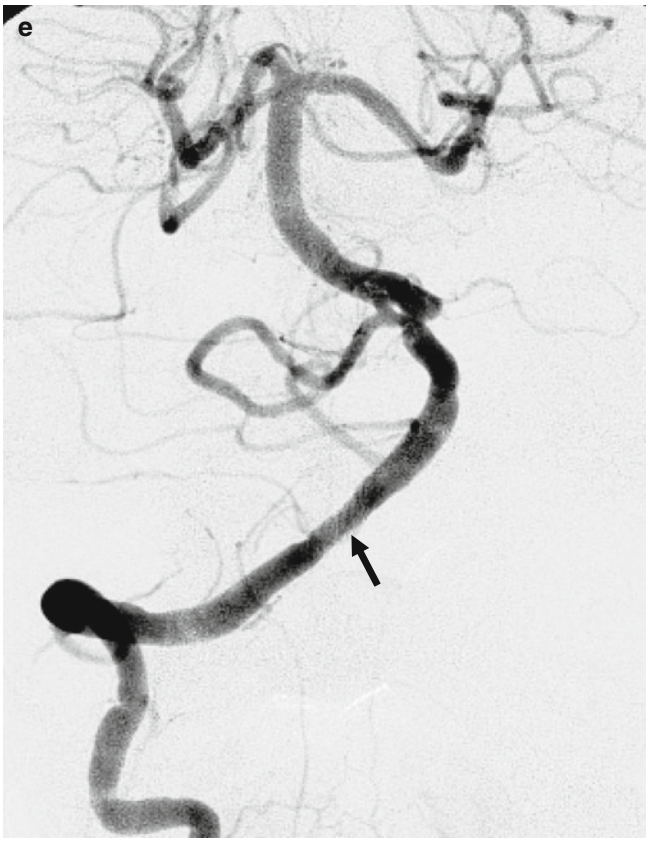

Fig. 1 (continued)

Discussion

Transient ischemic attacks of the posterior circulation are associated with a 22–35 % risk of stroke in 5 years, and infarction of the vertebrobasilar artery carries a serious prognosis [1, 5, 13]. WASID investigators suggest that 35–40 % of intracranial atherosclerosis cases involve the vertebrobasilar vessels [12]. Medical treatment, such as anticoagulation and antiplatelet aggregation therapy, does not consistently benefit patients. The annual vertebrobasilar territory stroke rate in nonsurgically treated patients with vertebrobasilar stenosis of at least 50 % was 8.7 % in the WASID study. In particular, symptomatic patients with hemodynamic compromise, such as the case presented here, cannot be expected to ameliorate the symptoms and prevent recurrent stroke with medical treatment. The limitations of standard medical treatment have encouraged the development of endovascular surgery for IAS. Currently there are three main endovascular procedures available for IAS: balloon angioplasty, angioplasty with a balloon-expandable stent, and balloon angioplasty with a self-expandable stent. Balloon angioplasty for vertebrobasilar artery stenosis was introduced in the early 1980s as an alternative to surgery by Sundt et al. [10]. The advantages of this procedure are straightforwardness and the ability to follow up noninvasively with MRA after treatment. However, its usefulness has been limited by immediate complications including elastic recoil, wall dissection, and vessel rupture [2, 6, 8, 11]. These limitations have fueled interest in treating these lesions using stents. Theoretically, stenting improves the acute and long-term patency and reduces the risk of acute closure from dissection by trapping plaque material between the stent and arterial wall. The advent of the self-expanding stent has enhanced the accessibility of the intracranial lesions and has increasingly been used for IAS [4, 7].

Recently, the results of the SAMMPRIS trial demonstrated a higher-than-expected 30-day stroke rate in the stent plus medical therapy arm (14.7 %), and a lower-than-expected 30-day stroke rate in the medical therapy alone arm (5.8 %). The difference in the 30-day stroke rate between the two arms was statistically significant [9]. In our series, technical success was achieved in all patients, and the rate of stroke and death within 30 days was 2.3 %. Our results of endovascular treatment were better than those of reported series [2, 4, 6–9, 11]. We can speculate on some of the reasons for our favorable result: (1) Under dilatation: The mean stenosis rate after endovascular treatment was greater than 15 % in the current study. Intracranial arteries are delicate and thin-walled vessels, with a greater risk of rupture, which can result in lethal bleeding [4, 7–10]. Therefore, we underdilate these arteries with or without stents. The relative under-dilatation can prevent lethal complications, such as subarachnoid hemorrhage. Indeed, there was no bleeding complication in our series. (2) Patient selection: The lesions we treated were accessible with coronary stents and short (>15 mm) lesions. The risk of periprocedural ischemic complications may be low in these patients, because of a small plaque volume, fewer perforators within the lesion, and fewer obstacles in the approach route to the lesion. (3) IAS of the vertebro-basilar arteries may be more suitable for endovascular treatment than that of the anterior circulation. In the SAMMPRIS trial, a considerable number of IAS cases involving anterior circulation were enrolled. The high complication rate of endovascular treatment influenced the poor outcome of the trial.

On the other hand, the restenosis rate after endovascular treatment was relatively high, accounting for 20 % of the patients. We speculated that the reasons for the relatively high restenosis rate were the small diameter of intracranial arteries and under-dilatation of the lesions to prevent vessel rupture. Restenosis may be an important cause of recurrent stroke. The early detection and appropriate therapy for restenosis could prevent recurrent stroke and improve the long-term results. Therefore, close clinical and neuroradiological follow-ups are essential for patients treated with endovascular surgery.

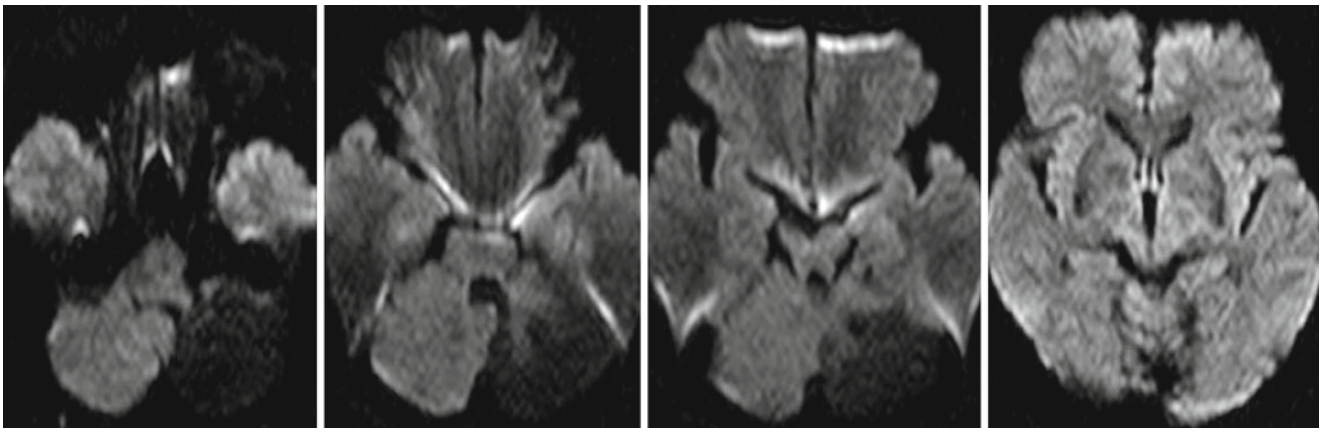

Fig. 2 MRI DWI imaging after stenting showing no fresh infarction

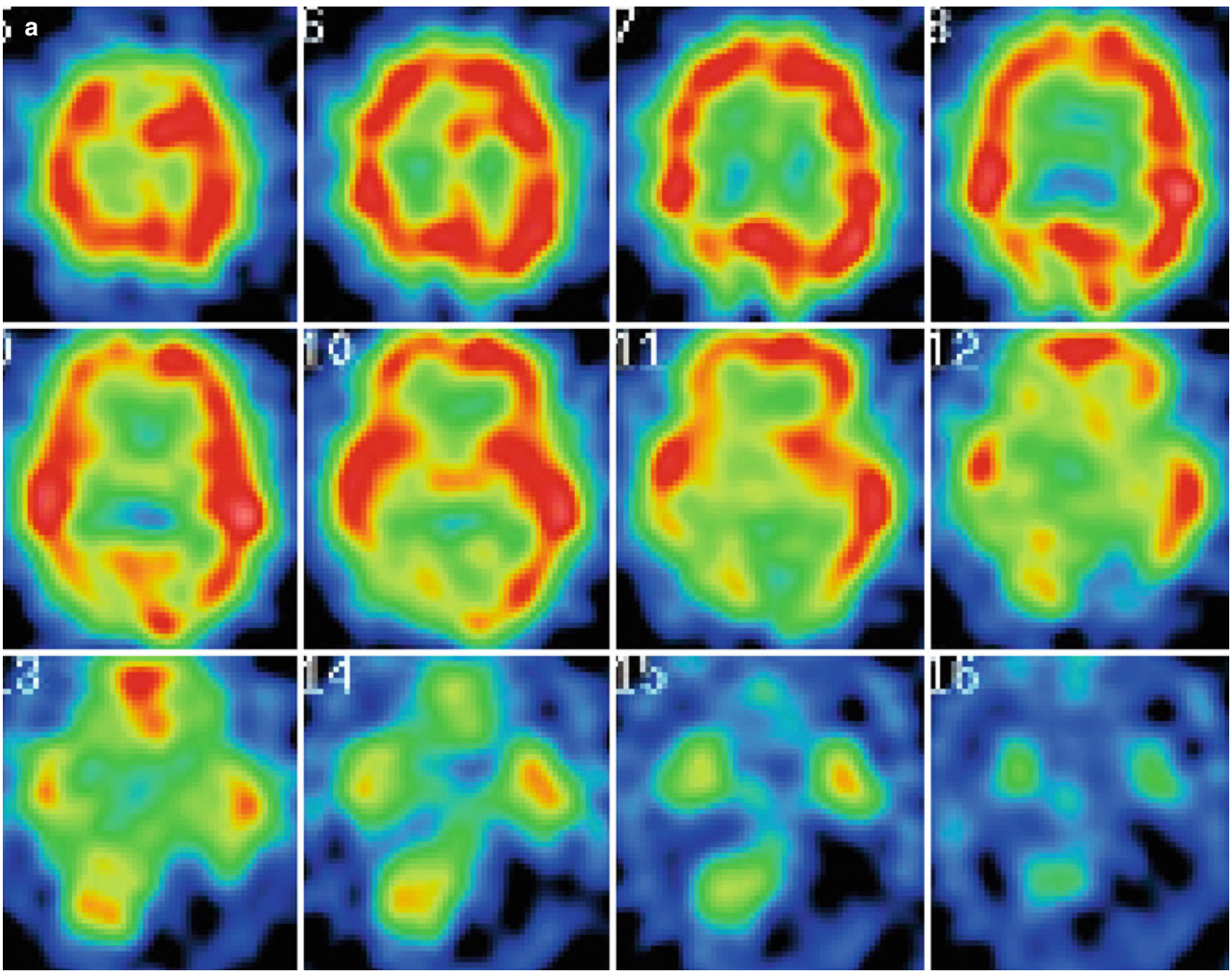

Fig. 3 (**a**) SPECT before treatment demonstrating a decline of cerebral blood flow in the cerebellum, brain stem, and bilateral occipital lobes. (**b**) SPECT after treatment demonstrating an increase of cerebral blood flow in the right cerebellum, brain stem and bilateral occipital lobes

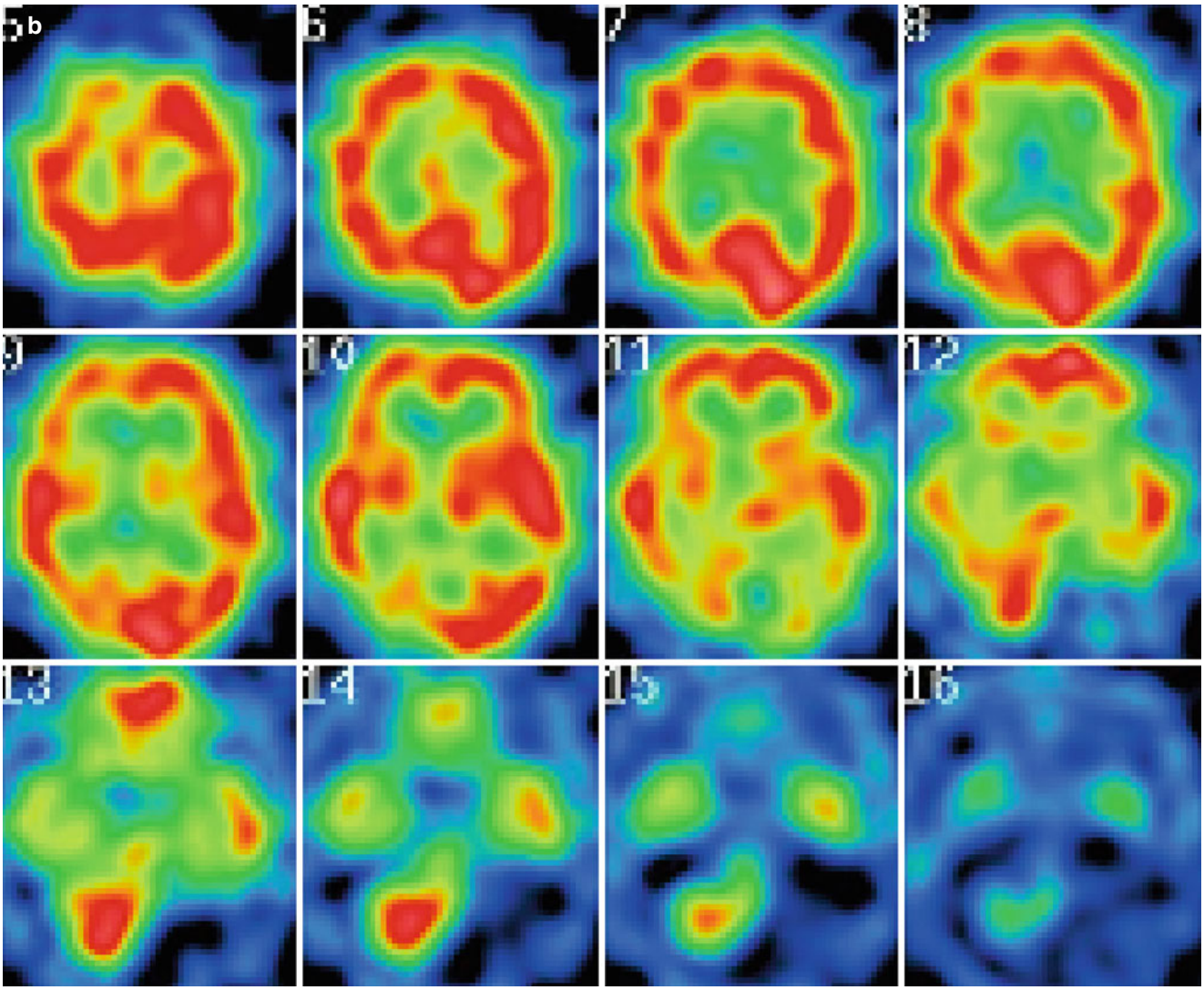

Fig. 3 (continued)

Conclusion

Endovascular surgery for intracranial vertebrobasilar artery stenosis is feasible and safe. Restenosis may be an important cause of recurrent stroke. Therefore, close follow-up is essential for patients treated with endovascular surgery to prevent recurrent stroke.

Conflict of Interest We declare that we have no conflict of interest.

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Carotid Endarterectomy for Pseudo-occlusion of the Cervical Internal Carotid Artery

Yoko Hirata, Noriyuki Sakata, Hirohito Tsuchimochi, Hitoshi Tsugu, Hirokazu Onishi, and Tooru Inoue

Abstract *Object*: This study described clinicopathological characteristics of pseudo-occlusion (PO) of the internal carotid artery (ICA) with regards to the pathological mechanism and the benefit of carotid endarterectomy (CEA).

Methods: We retrospectively reviewed 17 PO patients who underwent CEA. Clinical presentation, angiographic findings, surgical outcomes and plaque components obtained from CEA were investigated.

Results: PO plaques had more fibrous and two different pathological features, including total occlusion with recanalization and severe stenosis. Plaques of the total occlusion with recanalization (8 patients) were composed of thrombotic total occlusion and lumen recanalization by large neovascular channels, whereas those with severe stenosis (9 patients) were fibrous or fibroatheromatous plaque with severe stenosis of the original lumen. Of all the patients who underwent a carotid angiogram 2 weeks after surgery, 16 were successfully treated, but one showed complete occlusion of the ICA. At the follow-up period, two patients showed restenosis of the ICA. Three patients with complete occlusion or restenosis had histologically fibrous sclerotic plaques.

Conclusion: Patients with PO had more fibrous plaques and two different histological features, including total occlusion with recanalization or severe stenosis. The plaque histology may be related to the pathogenesis and the surgical outcome.

Keywords Internal carotid artery • Pseudo-occlusion • Carotid endarterectomy • Angiography • Histology • Vascular disease

Introduction

The term "pseudo-occlusion (PO)" of the internal carotid artery (ICA) was first used by Lippman et al. in 1970 [9]. It is defined as a severe stenosis of the ICA with an extremely narrow residual lumen and a collapsed distal portion induced by hypoperfusion [14]. Analyses of the North American Carotid Endarterectomy Trial (NASCET) and European Carotid Surgery Trial data have demonstrated that the stroke rate of PO is not high compared with that of severe stenosis without a collapsed distal portion. On the other hand, some papers have indicated that the natural course of PO is risky and emergent treatment is effective for PO [2, 7, 11, 15]. However, the use of the carotid endarterectomy (CEA) for PO is still uncertain with respect to the diagnostic procedures required, the risks, the appropriate timing, and the benefit of revascularization. In the treatment of atherosclerotic carotid stenosis, it is important to evaluate not only the stenosis but also the plaque characteristics as well as the pathogenesis. It has been thought that once severe carotid stenosis reaches the critical degree, the distal portion of the ICA begins to collapse and becomes PO [14], but the precise mechanism of PO has not yet been proven. We retrospectively reviewed 17 cases of PO patients who underwent CEA, with respect to clinical presentation, angiographic findings, surgical outcomes and plaque components. On the basis of the clinicopathological results, we also discuss the possible pathogenesis of PO and the benefit of CEA in this uncommon disease.

Y. Hirata, MD (✉) • H. Tsuchimochi, MD
H. Tsugu, MD • H. Onishi, MD
Department of Neurosurgery,
Japanese Red Cross Fukuoka Hospital, 3-1-1 Ookusu, Minami-ku,
Fukuoka city, Fukuoka 815-8555, Japan
e-mail: yokohirata@fukuoka-med.jrc.or.jp

N. Sakata, MD
Department of Pathology, Faculty of Medicine,
Fukuoka University, Fukuoka City, Japan

T. Inoue, MD
Department of Neurosurgery, Faculty of Medicine,
Fukuoka University, Fukuoka City, Fukuoka, Japan

T. Tsukahara et al. (eds.), *Trends in Neurovascular Interventions*, Acta Neurochirurgica Supplement, Vol. 119,
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Material and Methods

Study Population

A retrospective review of 345 patients undergone CEA (from January 2001 till December 2007) has been made. The indication for CEA was based on recommendations of the Asymptomatic Carotid Atherosclerosis Study/Asymptomatic Carotid Surgery Trial for asymptomatic patients and the NASCET for symptomatic patients. All patients underwent digital subtraction angiography (DSA) and PO of the ICA was defined, using the following angiographic criteria: (1) severe ICA stenosis with a collapsed distal ICA; (2) back filling of the ipsilateral carotid siphon via the ophthalmic artery in the early arterial phase; and (3) delayed anterograde flow of the patent ICA in the late arterial phase (Fig. 1). In addition, PO was distinguished from total occlusion of the ICA by conventional and transoral carotid artery ultrasonography, as previously reported [4].

Surgical Procedure and Postoperative Evaluation

Standard CEA techniques were utilized under general anesthesia. After the carotid bifurcation was exposed, the external carotid artery and common carotid artery were temporarily occluded, using clamps. The ICA was occluded as high as possible at the distal part and a longitudinal arteriotomy was done. Shunt use was based on the diameter of the collapsed distal ICA. Dissection and removal of the plaques and closure of the arteriotomy were performed under microtechniques. During the operation, a direct Doppler ultrasound scan was performed to detect pre- and postoperative blood flow volume. Perioperative management followed a protocol stipulated by Kyusyu Medical Center [3].

Atherosclerotic Plaque Analysis

The plaques were dissected from the bifurcation of the internal and external carotid arteries with CEA and fixed in 10 % buffered formalin. The specimens were transversely dissected into 3-mm-thick segments. Microscopic sections were cut from the paraffin-embedded tissue segments and stained with Hematoxylin and Eosin (H&E), elastica van Gieson (EVG), and Masson-trichrome (MT) for light microscopic examination. We observed the histological sections from all segments under a light microscope. To characterize the plaques, the lesion with the maximum degree of stenosis was subjected to histological evaluations. The percentage of atheromatous core of the total plaque area was visually estimated, with a division in three overall phenotypes: fibrous with a core of less than 25 %, fibroatheromatous with a core of 25–75 %, and atheromatous with a core exceeding 75 %. Plaque rupture, intraplaque hemorrhage, and fresh luminal thrombi were recorded as absent or present. Old organized thrombi were classified into absent, non-occlusive, or occlusive. Plaque analysis was performed by two pathologists (Y.H. and N.S.) who were blinded to the patient's clinical information. Both pathologists

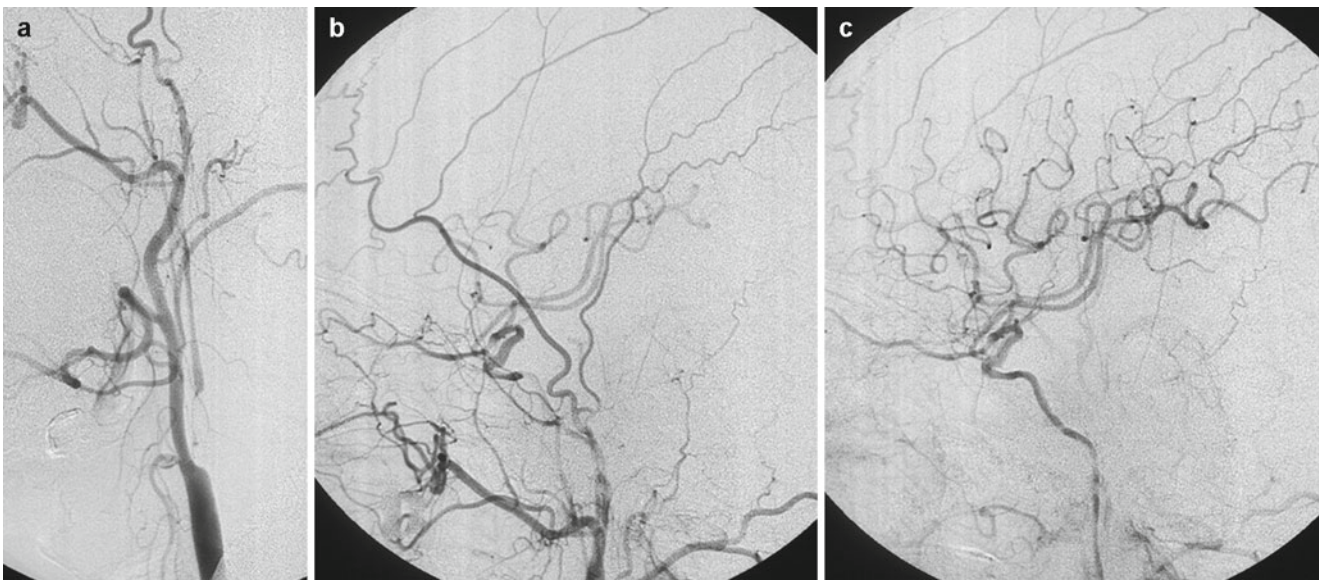

Fig. 1 Angiographic pseudo-occlusion criteria of the ICA. (**a**) Severe stenosis of the ICA with a collapsed distal ICA. (**b**) Back filling of the ipsilateral carotid siphon via the ophthalmic artery. (**c**) Delayed antegrade flow of the patent ICA in the late arterial phase

independently performed semiquantitative analysis and the mean numerical values obtained from them was used for plaque analysis. Discrepancies were rare in the semiquantitative data between pathologists.

Postoperative Evaluations and Follow-up

Computed tomographic (CT) and magnetic resonance imaging (MRI) scans were performed in all patients within 1 week of surgery to evaluate the ischemic or hemorrhagic lesions related to the revascularization. In addition, DSA was performed 2 weeks after surgery in all patients. At follow-up periods, all patients were advised to undergo MRI and ultrasound 3 months after surgery and every year thereafter. Clinical data, including the atherosclerotic risk factors, neurological presentations, angiographic findings, and surgical outcomes, were derived from hospital records. This study was performed in compliance with protocols stipulated by the Fukuoka University Faculty of Medicine, Human Research Subject Committee, and Kyusyu Medical Center Research Committee.

Results

Characteristics of Study Population

Of the 345 patients, 17 (4.9 %) satisfied the diagnostic criteria for PO of the ICA. The mean age of patients was 70.5 years, and 2 of the patients were women. Sixteen patients had hypertension, 7 had diabetes mellitus, 9 had hyperlipidemia, 2 had peripheral arterial disease, and 5 had ischemic heart disease. Four patients (23.5 %) were neurologically asymptomatic, 7 (41.2 %) had suffered a transient ischemic attack, and 6 (35.3 %) had had a minor stroke. Angiographically, ACoA-PCoA collateral flow pattern developed in 7 patients (41.2 %), ACoA/PCoA pattern in 7 patients (41.2 %), and leptomeningeal pattern in 3 patients (17.6 %). The mean time interval between the latest ischemic event and surgery in symptomatic patients was 2.2 months. Complete follow-up data (mean 20.2 months) were available for all 17 patients.

Intraoperative Findings

All atheromatous lesions were located at the origin of the ICA. Using a Doppler ultrasound microprobe during surgery, direct blood flow of the collapsed distal ICA could be detected in all patients. After arteriotomy, all atherosclerotic plaques were not extended more distally and could be exposed clearly. Retrograde sufficient blood flow was detected and a temporary intraluminal shunting was used in all procedures. A direct suture of the ICA, without patch technique, was performed in each patient. A direct Doppler ultrasound signal was registered at the end of surgery, and postoperative sufficient blood flow was detected in all patients. All procedures were successfully done with standard CEA techniques and there were no surgical complications.

Histopathological Findings

The plaques obtained from the PO patient demonstrated more fibrous sclerotic phenotypes. Of all 17 patients, the fibrous or fibroatheromatous plaques were present in 14 patients (82.4 %). The incidence of plaque rupture was high in PO patients (64.7 %). Nine patients (52.9 %) had intraplaque hemorrhage, 8 (47.1 %) had fresh luminal thrombi, and all had old organized thrombus. Of all 17 old organized thrombus, nonocclusive thrombus was found in 9 patients (52.9 %) and occlusive thrombus was in 8 plaques (47.1 %). In other words, PO had two different histological features, the presence or absence of the true lumen. Plaques of total occlusion with recanalization (8 patients) were thrombotic occlusion with lumen recanalization by large neovascular channels (Fig. 2a, b), while those of severe stenosis (9 patients) were fibrous or fibroatheromatous with severe stenosis of the original lumen (Fig. 2c, d).

Surgical Outcome and Follow-up

No new ischemic or hemorrhagic lesions were found on CT or DWI MRI within 1 week of surgery. Of all 17 patients who underwent DSA 2 weeks after CEA, 16 patients (94.1 %) were successfully treated, and we observed satisfactory dilatation of the ICA. In one case (5.9 %), (symptom free), we noted complete occlusion of the ICA and underwent superficial temporal artery-middle cerebral artery anastomosis. During the follow-up periods, 2 patients (11.8 %) showed restenosis of the ICA. One patient had suffered transient monocular blindness 8 months after surgery and an immediate DSA demonstrated moderate stenosis of the ICA. Another patient was symptom-free and restenosis was detected on MRA and ultrasound 12 months after surgery. Both patients were treated with carotid artery stenting, resulting in satisfactory dilatation. Three patients with complete occlusion or restenosis of the ICA had histologically more fibrous sclerotic plaques.

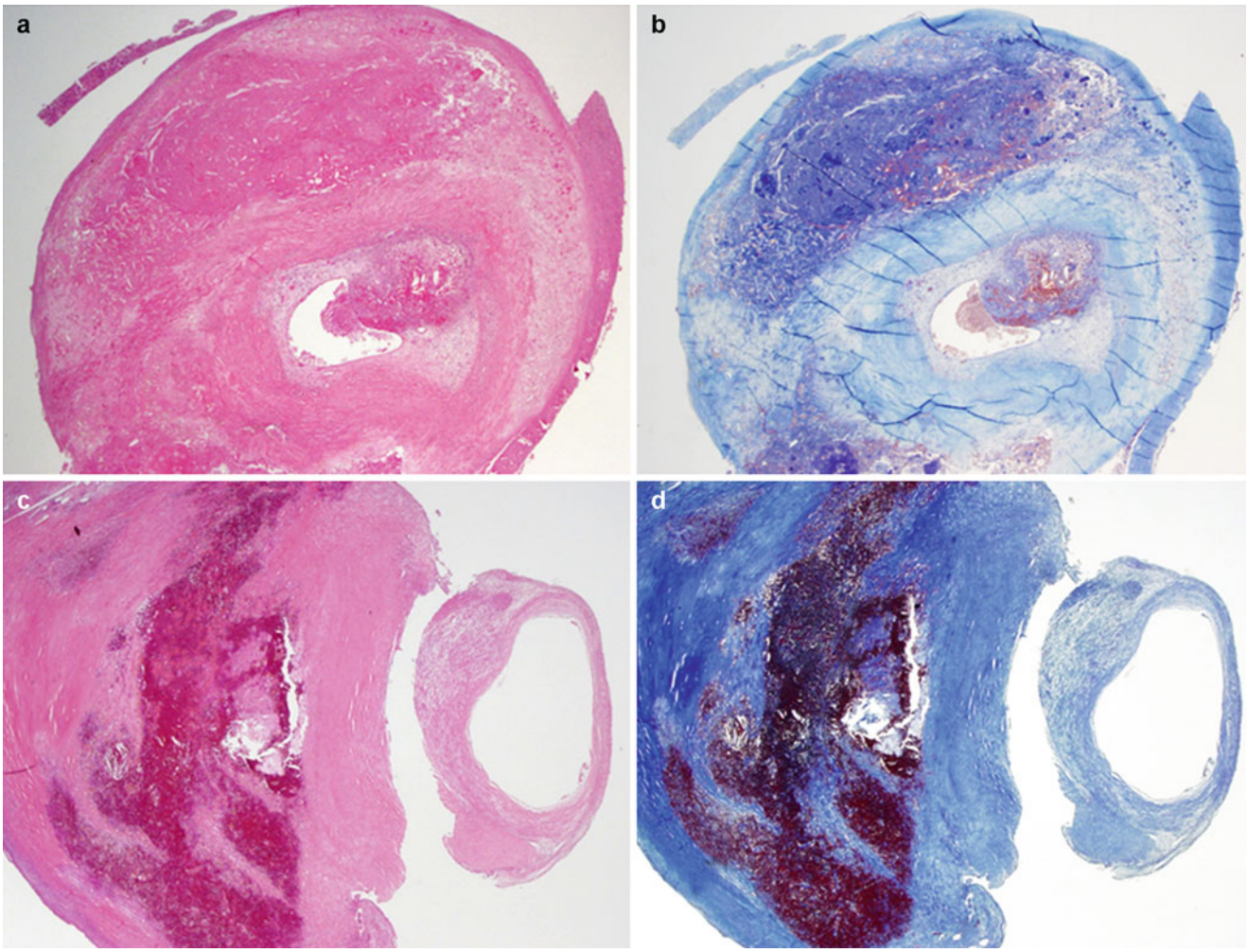

Fig. 2 Representative photographs of carotid artery pseudo-occlusion plaques showing two different features. (**a**, **b**) A patient with pseudo-occlusion without true lumen has thrombotic organized total occlusion of the ICA with recanalization by neovascular channels. (**c**, **d**) A patient with pseudo-occlusion with true lumen has hard plaque with severe stenosis consisting mainly of fibrous tissue accompanied by intraplaque hemorrhage. H&E (**a**, **c**) and MT (**b**, **d**)

Discussion

The aim of this study was to discuss the pathogenesis of PO and whether CEA could be an effective treatment for PO, based on the clinicopathological results. Our findings indicate that the PO plaque compositions may be one of the factors, causing reduction of the flood flow and collapsed distal portion. Alternatively, PO is a lesion treatable by CEA with minimum risk and a high success rate, and the plaque histology can be related to the surgical outcome. It is widely accepted that primary carotid artery stenotic lesions are caused by advanced atherosclerosis [8, 16]. The rupture of unstable plaques, characterized as having a large atheromatous core, thin fibrous cap, and infiltration of inflammatory cells, causes thrombotic events and is followed by plaque stabilization, including reorganization and fibrosis, over time [12]. In our group, plaque rupture and intraplaque hemorrhage were detected in approximately 50 % or more, which was compatible with other reports [8, 16], although fibrous or fibroatheromatous plaques were prevalent, and old organized thrombi were frequently found in the PO patients. These findings indicate that considerable time had passed since the initial thrombotic events. PO plaques had two subtypes of old organized thrombi, occlusive or non-occlusive of the original lumen; in other words, PO had two different histological features. Plaques of the total occlusion with recanalization (8 patients, 47.1 %) were composed of thrombotic total occlusion and lumen recanalization by large neovascular channels, whereas those of severe stenosis (9 patients, 52.9 %) were fibrous sclerotic plaque with severe stenosis of the original lumen. It is interesting to speculate as to why the PO falls into collapse and not into complete occlusion, despite severe stenosis. The abrupt increase in the degree of stenosis, reducing blood flow and collapse of the distal ICA, could be explained by either disrupted intraplaque hemorrhages with some connection to the arterial lumen or expanded intraplaque hemorrhages without

plaque disruption or luminal extension [1, 16]. Plaques of the total occlusion with recanalization could be structured by the luminal thrombi arising from intraplaque hemorrhage with plaque disruption. On the other hand, plaques of severe stenosis might be formed by subluminal hemorrhages without plaque disruption or luminal extension. However, various clinicopathological features may occur, depending on the degree of stenosis, the site, and the plaque compositions [1, 13]. The angiographic appearance of PO may be caused not only by the severity of stenosis but also by plaque compositions. Changes in plaque compositions from atheromatous to fibrotic may reduce the intraluminal pressure and collapse the ICA distal portion. Symptomatology, acute occlusive thrombosis of the carotid arteries may be either asymptomatic or present with only mild symptoms if the Circle of Willis or other intracranial collateral circulation is adequate, as in our cases. This finding suggests that the adequate collateral flow plays an important role in maintaining the intraluminal blood pressure and delayed anterograde flow of the patent ICA. The natural history of PO of the ICA is obscure. A success rate of revascularization for PO was reported from 75.0 to 100 % in previous literature [5]. Several authors have described that CEA for PO is less beneficial. However, Morgenstern et al. reported that surgery for PO was indeed of benefit and resulted in a reduction of the stroke rate [10]. In our series, of all 17 patients, 16 (94.1 %) were successfully treated without perioperative complications. Our surgical results were also favorable compared with other previous reports. Of all 17 patients, 1 (5.9 %) showed occlusion of the ICA on DSA 2 weeks after surgery. Greiner et al. pointed out that frequent causes for failure of reconstruction are hypoplastic or fibrotic vessels, chronic subtotal thrombosis, or simply too long an interval between the initial diagnosis and intra-operative evaluation [5]. The present case involved a histologically fibrous plaque with severe stenosis, indicating that progression of atherosclerosis extended to the distal ICA and the fibrotic vessel wall could prevent satisfactory dilatation of the ICA. During the follow-up periods, restenosis was encountered in two patients (11.8 %), and they were successfully treated with CAS. Hellings et al. described that plaque composition is an independent predictor of restenosis after CEA and a lipid-rich, inflammatory plaque is associated with a reduced risk of restenosis [6]. In our study, two plaques with ICA restenosis were fibrous, indicating that the plaque compositions might be useful to identify a patient with restenosis after surgery. Recently, CAS has been developed as an alternative treatment to CEA in carotid atherosclerotic disease, and the advantages and disadvantages of each procedure are currently under discussion. Terada et al. described that CAS for PO under embolic protection was beneficial and resulted in a reduction of the stroke rate [15]. The indications for carotid artery revascularization have been basically determined by the degree of stenosis, but it is important to evaluate the plaque compositions. We demonstrated that PO plaques had two different histological features, including the thrombotic occlusion with recanalization or severe stenosis. Plaques of severe stenosis could be treatable with CEA or CAS; in contrast, those with total occlusion with recanalization, in the absence of true lumen, could be suitable for CEA because it seemed to be difficult for endovascular devices to pass through the arterial lumen.

Our study has several limitations. First, we examined CEA specimens and evaluated the plaque histology of only the segment with the most severe stenosis in the culprit lesions. Second, angiogram was not performed repeatedly to obtain the evidence that carotid arteries had completely occluded and then later recanalized. Finally, our findings are based on a small group of patients and our data need confirmation in large studies in other populations. In conclusion, the present study revealed that PO plaques had more fibrous and two different histological features, including total occlusion with recanalization or severe stenosis. The plaque compositions may be one of the factors causing the reduction of blood flow and collapse of the distal ICA. PO of the ICA is a treatable lesion by CEA with minimum risk and a high rate of success, and the plaque histology could be related to the surgical outcome.

Conclusion

In conclusion, the present study revealed that PO plaques had more fibrous and two different histological features, including total occlusion with recanalization or severe stenosis. The plaque compositions may be one of the factors causing the reduction of blood flow and collapse of the distal ICA. PO of the ICA is a treatable lesion by CEA with minimum risk and a high rate of success, and the plaque histology could be related to the surgical outcome.

Conflict of Interest We declare that we have no conflict of interest.

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Identification of Plaque Location Using Indocyanine Green Videoangiography During Carotid Endarterectomy

Masakazu Okawa, Hiroshi Abe, Tetsuya Ueba, Toshio Higashi, and Tooru Inoue

Abstract *Background and Aims*: The aim of the present study was to assess whether surgical microscope-based indocyanine green (ICG) videoangiography (ICG-VA) using FLOW 800 software provides useful evaluation of blood flow during carotid endarterectomy (CEA).

Methods: Twenty CEA procedures were performed in 19 patients between July 2011 and January 2012. ICG was injected intravenously before and after CEA, and ICG-VA video sequences were analyzed using FLOW 800. Regions of interest were identified in the common carotid artery, plaque, internal carotid artery, and external carotid artery, and changes in intensity values were evaluated.

Results: The distal and proximal ends of the carotid plaque were identified in 87.5 and 75 % of cases, respectively. After CEA, intensity values in the common carotid artery, plaque, internal carotid artery, and external carotid artery had increased by 162 ± 129, 337 ± 212, 139 ± 151, and 177 ± 143, respectively. The intensity values in the region of the plaque showed the greatest improvement.

Conclusions: ICG-VA can provide information regarding plaque location vessel patency during CEA. FLOW 800 software provides semiquantitative information regarding blood flow, especially in cases of severe stenosis with collapse of the internal carotid artery.

Keywords Carotid endarterectomy • Indocyanine green videoangiography • Plaque • FLOW800

M. Okawa, MD (✉) • H. Abe • T. Ueba, MD
T. Higashi • T. Inoue, MD
Department of Neurosurgery, Faculty of Medicine,
Fukuoka University, 7-45-1 Nanakuma, Jounan-ku,
Fukuoka City, Fukuoka 814-0180, Japan
e-mail: okawam@fukuoka-u.ac.jp; tueba@fukuoka-u.ac.jp

Introduction

Indocyanine green videoangiography (ICG-VA) provides a simple and quick method of visualizing vascular structures during microsurgical procedures. Raabe et al. [5] were the first to describe the use of ICG-VA for intraoperative assessment of cerebral vascular flow, enabling visualization of vessel patency and aneurysm occlusion during aneurysm surgery. The usefulness of this procedure has been documented for both vascular surgery, such as extracranial-intracranial bypass, aneurysm clipping, and arteriovenous malformation surgery, and tumor surgery [5–7, 9, 10]. Only a few reports have described the efficacy of ICG-VA in carotid endarterectomy (CEA) [1–4]. The aim of our study was to determine the usefulness of ICG-VA for localizing plaque and confirming the patency of the internal carotid artery during CEA.

Methods

Patient Population

Nineteen patients who underwent 20 CEA procedures at Fukuoka University between July 2011 and January 2012 were included in this study. The patients were 15 men and 4 women with a mean age of 72 years (range, 60–86 years). Ten of the lesions (50 %) were symptomatic. The mean stenotic ratio was 80.5 ± 11.8 % using the NASCET method.

Carotid Endarterectomy

Conventional CEA was performed under general anesthesia, using an operating microscope and electroencephalographic monitoring. Shunts were used in all patients when the carotid artery was interrupted. No patients underwent patch closure.

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Indocyanine Green Videoangiography

Intraoperative ICG-VA was performed using a surgical microscope (Carl Zeiss Co., Oberkochen, Germany) with integrated INFRARED 800. The operative field was illuminated by a light source with a wavelength covering part of the ICG absorption band (range, 700–850 nm). A vial of ICG dye (25 mg) was reconstituted in 4 ml of saline, and 1 ml (6.25 mg) was injected into a central vein as a bolus followed by a 20-ml bolus of saline. ICG-VA was performed twice for every procedure – before and after CEA.

Analysis Using FLOW 800 Software

FLOW 800 software (Carl Zeiss Co., Oberkochen, Germany) is an analytical visualization tool for the rapid and reliable interpretation of the fluorescence video sequences generated using INFRARED 800. We used this software to analyze the ICG-VA sequences obtained intraoperatively. The time-intensity maps and diagrams were recorded and analyzed. Changes in intensity values were evaluated in regions of interest in the common carotid artery, plaque, internal carotid artery, and external carotid artery.

Data Analysis

Data were analyzed using the SPSS 14.0.J program (SPSS Inc., Chicago, IL, USA). Intensity values before and after endarterectomy were compared using the student's *t*-test.

Results

The distal and proximal ends of the carotid plaque were identified in 87.5 and 75 % of patients, respectively, before endarterectomy. In three cases, arterial waves could not be detected in the internal carotid artery using Doppler ultrasonography, but blood flow was detected using ICG-VA. In one of these three cases, the distal end of the plaque was identified by retrograde flow. Patency of the internal carotid artery was confirmed after endarterectomy in all cases. After endarterectomy, the intensity values in the common carotid artery, plaque, internal carotid artery, and external carotid artery had significantly increased to 162 ± 129, 337 ± 212, 139 ± 151, and 177 ± 143, respectively. These values represented substantial improvement, especially in the region of the plaque (Fig. 1).

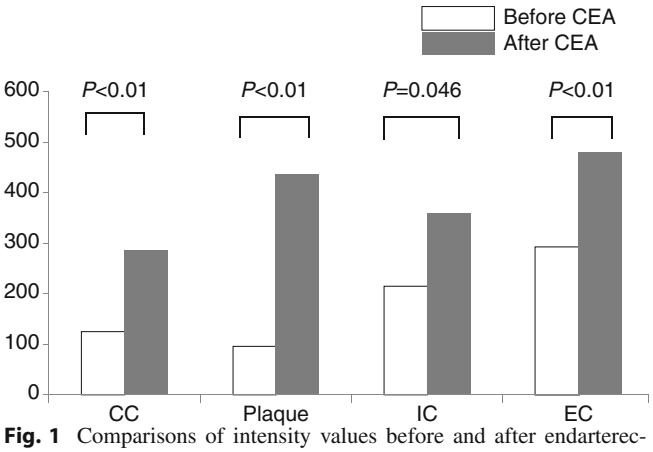


Fig. 1 Comparisons of intensity values before and after endarterectomy. Intensity values increased significantly in each region of interest after endarterectomy, especially in the region of the plaque

Case Presentation

A 70-year-old woman with a history of hypertension was shown to have left internal carotid artery stenosis on carotid ultrasonography. Carotid angiography showed a 64.0 % stenosis using the NASCET method. Carotid endarterectomy was performed using a shunt. Before CEA, ICG-VA showed a lower intensity value in the region of the plaque than in other regions, with a slight increase in intensity in the late phase because of the vasa vasorum (Fig. 2a–d). The time-intensity curve did not document a peak in the region of the plaque. After CEA, these abnormalities diminished and internal carotid artery patency was confirmed (Fig. 2e–h).

Discussion

Our results show the efficacy of using ICG-VA during CEA. We were able to identify the plaque before CEA as a region of relatively low intensity on ICG-VA [3]. This was especially useful for determining whether the distal end of the plaque was located in the internal carotid artery. As we routinely use a shunt during CEA, it is important to perform adequate dissection for shunt placement. In three cases we were not able to confirm blood flow in the distal part of the internal carotid artery using ultrasonography, but were able to identify the distal end of the carotid plaque using ICG-VA. We were able to confirm patency of the internal carotid artery after CEA in all cases using ICG-VA. Blood flow can also be assessed intraoperatively using ICG-VA. In one case in which the internal carotid artery was perfused via retrograde flow, cerebral angiography had indicated antegrade flow. As ICG is administered intravenously, blood flow might be shown more accurately than in cerebral angiography where the contrast agent is administered via the carotid artery.

When using FLOW 800, the intensity diagram function helps to visualize the variation in blood flow over time. We can freely define which regions of interest are to be evaluated. The locations of plaques are shown as low intensity (dark) regions. After CEA, the intensity values of all regions increased significantly. We assumed that intensity values

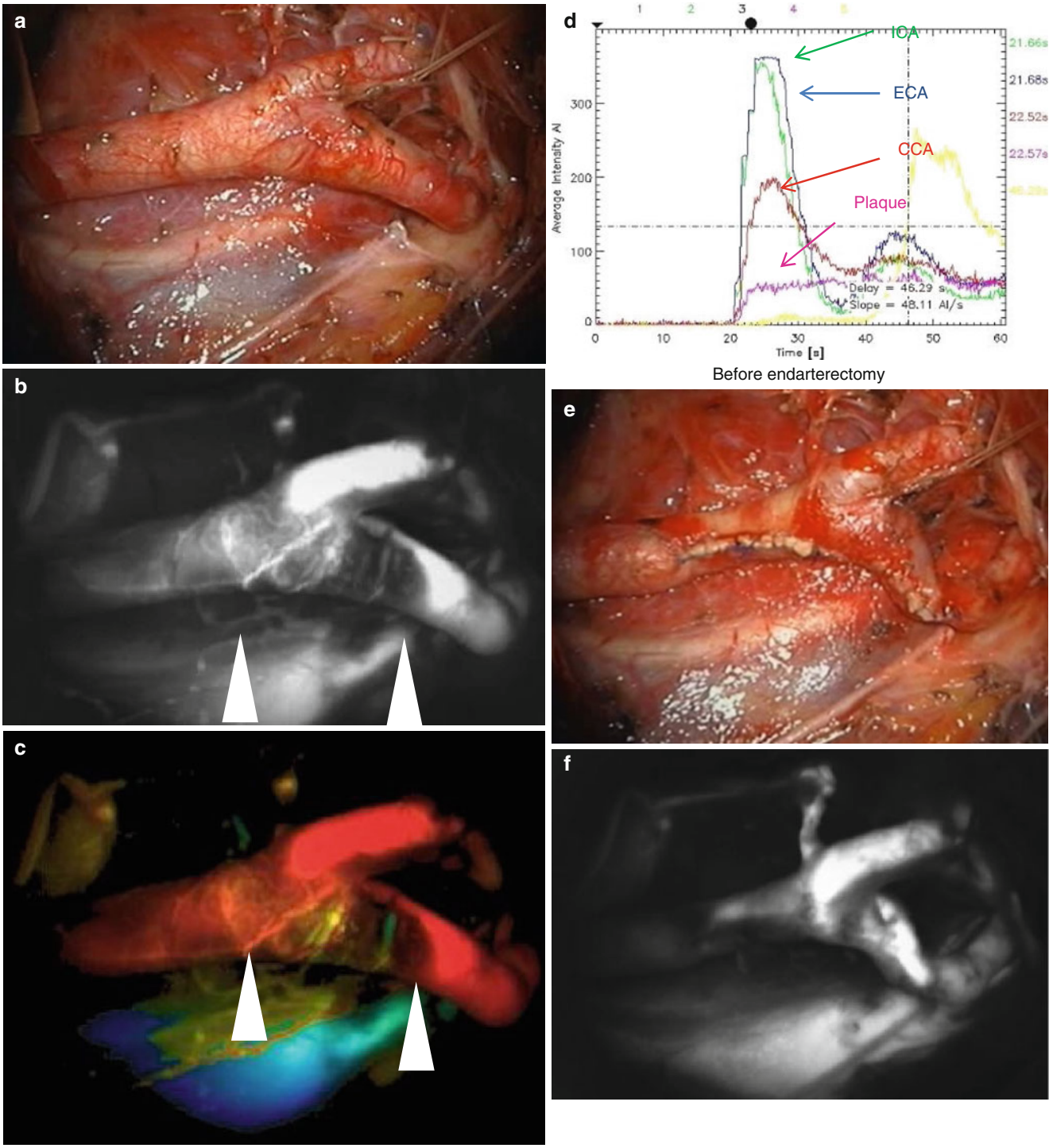
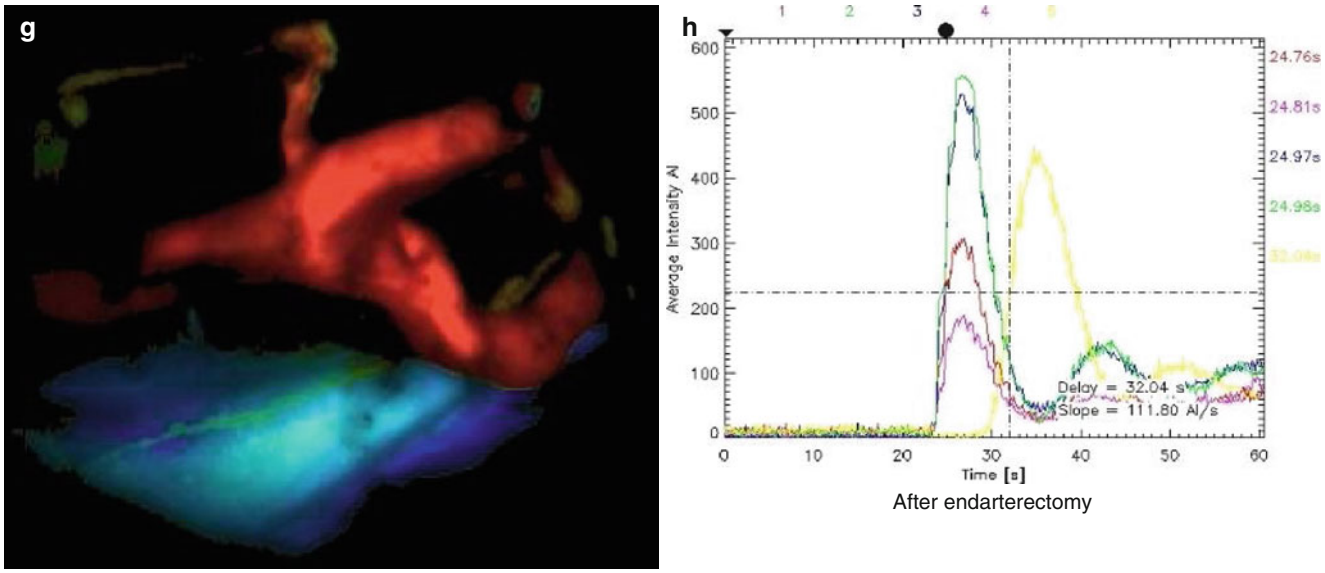


Fig. 2 (**a**–**d**) Before CEA. (**e**–**h**) After CEA. (**a**, **e**) Surgical views. (**b**, **f**) Maximum-intensity maps. (**c**, **g**) Time-intensity maps. (**d**, **h**) Time-intensity curves. (**b**, **c**) Show the location of the plaque as a dark area (*arrowheads*). (**d**) Before CEA, the plaque caused flattening of the *pink curve*. (**f**–**h**) The examination findings improved after CEA



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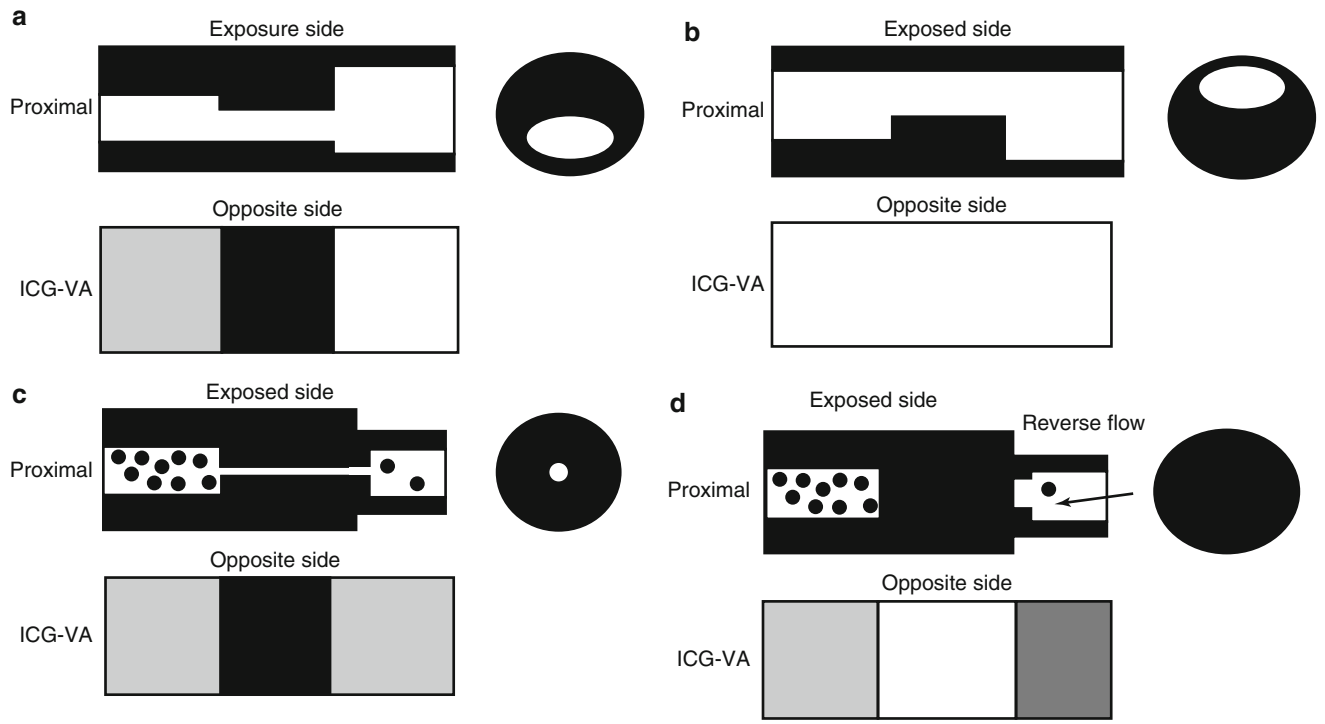

Fig. 3 Schematic diagram showing ICG-VA results depending on plaque location and the degree of stenosis. (**a**) If the plaque is mainly on the side of exposure, ICG-VA shows a decrease in the intensity value. (**b**) If the plaque is mainly opposite the side of exposure, ICG-VA does not show a decrease in the intensity value, and the plaque is not seen. (**c**) If the stenosis is severe but not occlusive, there is antegrade flow, and the intensity value is low in the distal internal carotid artery because of decreased blood flow. (**d**) If the stenosis is occlusive, the flow is retrograde

would inversely correlate with the thickness of the arterial wall at the surgical site (Fig. 3). The thickened wall at the site of the plaque showed as a low intensity region as the near-infrared light did not pass through easily, while the thin wall of the artery after CEA showed as a high intensity region. In some cases with high-grade stenosis, ICG-VA did not reflect the wall thickness because the decreased blood flow delivered only a small of amount of ICG, resulting in flattening of the time-intensity curve analyzed by FLOW 800.

There are some disadvantages to using ICG-VA. The choice of injection route is important. Tseng et al. [8] reported dilution due to injection into a left arm vein and reflux of contrast agent into the neck veins during computed tomography angiography of the carotid arteries, and the same would apply to injection of ICG. There is also some risk of dye leakage when a peripheral injection site is used. We injected ICG into a central vein to avoid these problems. Care should be taken to ensure hemostasis. Fluorescent materials used during surgery, such as sutures and vessel tapes, may also interfere with the view.

There are several limitations to using ICG-VA during CEA. This method cannot evaluate the inner lumen or the friability of the plaque. In some cases the plaque was deeply ulcerated, which may have interfered with the evaluation of ulcers located on the side of surgical exposure. FLOW 800 analyzes the change in the intensity value over time, but does not measure blood flow, and therefore cannot be used to determine hyperperfusion.

Conclusion

ICG-VA can be used during CEA to confirm plaque location, especially in cases with a severe distal stenosis that acts as a pseudo-occlusion. The thickness of the carotid artery wall and the degree of stenosis influence the intensity values during ICG-VA. We were able to confirm patency of the internal carotid artery during CEA in all patients.

Conflicts of Interest We declare that we have no conflict of interest.

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Arteriovenous Malformations, Cavernomas, Developments in Cerebrovascular Imaging

Surgery After Embolization of Cerebral Arterio-Venous Malformation: Experience of 123 Cases

A. Pasqualin, P. Zampieri, A. Nicolato, P. Meneghelli, F. Cozzi, and A. Beltramello

Abstract A group of 123 patients with large or critically located arterio-venous malformations (AVMs), operated on between 1990 and 2011 and who underwent preoperative embolization, was assessed in order to clarify the risks of this combined treatment. AVM location, volume, and Spetzler's grade were assessed in each case; AVM volume was over 20 cm^3 in 49 % of the cases; Spetzler's grade was 3 or above in 76 % of the cases (with 34 cases in grades 4–5). A mean of 2.3 embolization procedures per patient were carried out, using bucrylate and, more recently, Onyx and/or Glubran; a 4.5 % procedure-related complication rate was observed. Complications occurring after surgery were classified as hemorrhagic (16 cases, 8 requiring surgical evacuation) or ischemic (4 cases); hemorrhagic complications were more common for AVMs with volumes >20 cm^3 and/or deep feeders. Surgery-related unfavorable results (modified Rankin Score > 2) were observed in 6 % of patients in Spetzler's grade 3, and in 20–25 % of patients in grades 4–5. More recently, a triple treatment (radiosurgery + embolization + surgery) allowed for obtaining favorable results (mRS 0–2) in all patients. It has been concluded that a combined treatment with embolization and surgery constitutes a reasonable choice for complex cerebral AVMs; the association of radiosurgery may improve the patients outcome.

Keywords Critical cerebral AVMs • Embolization • Onyx • Microsurgery • Deep feeders • Radiosurgery • Radionecrosis • AVM volume

A. Pasqualin (✉) • A. Nicolato • P. Meneghelli • F. Cozzi
Section of Vascular Neurosurgery, Institute of Neurosurgery, Verona City Hospital, Via Milazzo, 2, 37128 Verona, Italy
e-mail: albertopasqualin@tin.it

P. Zampieri • A. Beltramello
Service of Neuroradiology, Verona City Hospital, Verona, Italy

Introduction

The treatment of complex cerebral AVMs remains a matter of controversy, owing to the uncertain natural course for many of these lesions [16, 25] and to the significant surgical risks. The introduction of radiosurgery – as a substitute for surgery – has not yet produced satisfactory results in large series [3, 13, 22]. Although preoperative embolization remains a reasonable choice for treatment of these AVMs, this procedure is not without risks [19, 24].

The aim of this paper is to review our experience with combined embolization and surgery in the management of complex cerebral AVMs.

Materials and Methods

Out of a total of 280 patients operated on for cerebral AVMs in our institute between 1990 and 2011, 123 cases underwent also preoperative embolization: these patients constitute the material of this study. Among these 123 patients, four of these patients were operated on for large hematomas while they were comatose. A subgroup of 19 patients previously submitted to radiosurgery are also considered. In this subgroup, reasons for additional surgery were (1) scant angio changes after radiosurgery (in 9 cases); (2) radionecrosis after radiosurgery in 7 cases (in 5, also with cyst formation); and (3) hemorrhage from residual AVM after radiosurgery in 4 cases.

There were 69 males (56 %) and 54 females (44 %); the mean age was 33.2 years (ranging from 9 to 63 years). Clinical presentation was constituted by epilepsy in 75 cases (61 %); of these, 5 patients also experienced hemorrhage before surgery; 35 cases (28 %) presented with hemorrhage; 11 cases (9 %) presented with headache, and 6 cases (5 %) with other disturbances (or represented an incidental discovery). All patients were carefully assessed with magnetic resonance imaging (MRI) and angiography, defining – according to our classification [18] – AVM location and

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maximum diameter; AVM volume (calculated from the multiplication of the three orthogonal diameters and divided by two); AVM feeders (superficial versus deep); AVM drainage (superficial versus deep); and extent of the draining system (in 4 grades, according to our classification) [18]. As regards AVM volumes, this was between 1 and 10 cm^3 in 15 patients, between 11 and 20 cm^3 in 48 patients, between 21 and 30 cm^3 in 28 patients and over 30 cm^3 in 32 patients. Applying the Spetzler and Martin scale [23], 30 patients were grade 1 or 2, 59 patients were grade 3, 26 patients were grade 4 and 8 patients grade 5.

A total of 286 procedures of embolization were carried out on these patients before surgery (a mean of 2.3 procedures/patient); most patients (86 cases) were treated with bucrylate, 34 with Onyx and/or Glubran, and 4 with coils and suture threads [2]. Seventy-seven patients (63 %) were operated on within 20 days of their last embolization, and the remaining were operated on later than that.

Surgery was planned after confirmation that flow through the malformation was significantly reduced in the individual cases, and that further embolization could carry an unreasonable risk for the patient. As described in a previous paper by our group [19], the amount of intraoperative blood loss (<2,000 cc <) was recorded, as well as the presence of hyperemia at the edge of the nidus or in the paraventricular area. Particular care was taken in the control of blood pressure in the immediate postoperative period, maintaining systolic blood pressure <120 mmHg in all cases (and using Labetalol or Urapidil in refractory patients). All patients were submitted to post-operative angiography before discharge in order to confirm the complete removal of the AVM.

One or more clinical evaluations were performed at follow-up, ranging from 1 to 21 years (mean follow-up was 13.3 years). Clinical outcome was assessed through the modified Rankin Scale (mRS), and divided into favorable (mRS 0–2) versus unfavorable (mRS > 2).

The following risk factors were related to outcome: (1) AVM location; (2) AVM volume; (3) AVM feeders; (4) AVM Spetzler and Martin grade. Statistical analysis was performed using the chi-square test and the Fisher exact test if the sample size was too small.

As mentioned before, a detailed analysis of outcome was also carried out in a subgroup of 19 patients (15.4 % of the total number) submitted to radiosurgery years before surgery. The reasons for surgery, average radiation dose at periphery, and average interval from radiosurgery to surgery are presented in Table 1.

Results

Following embolization, 6 patients presented transient deficits (disappearing within 2 weeks); 5 patients experienced ischemic complications and 8 patients hemorrhagic complications (Fig. 1.); in 7 other patients, hemorrhage occurred months after embolization. Permanent morbidity due to embolization is shown in Table 2.

During surgery, 24 patients (19 %) were considered to have significant hyperemia at the edge of the nidus; in 14 of them, the AVM volume was >20 cm^3. In 26 patients (21 %), prolonged paraventricular bleeding was faced during surgery; in 20 of them, the AVM volume was >20 cm^3.

Postoperative complications consisted mainly of postoperative hemorrhages (16 cases, 8 of which required decompression). AVM volume >20 cm^3 and deep feeders were significantly related with the incidence of prolonged paraventricular bleeding and post-operative hematoma (both considered to be hyperhemic complications) (Table 3). On the whole, the AVM was over 20 cm^3 in 10 out of 16 patients with postoperative hematomas (and with deep feeders in 6 cases); the AVM had volume <20 cm^3 and deep feeders in 4 patients. Postoperative ischemic complications were observed in only 4 cases – 2 with arterial supply from the anterior choroidal artery, 1 from the posterior communicating artery, 1 from the posterior cerebral artery, and in 3 cases, AVM volume was >20 cm^3, in one 13 cm^3.

Surgery-related outcome is presented in Table 4, according to the Spetzler and Martin grade; for more detailed analysis, grade 3 patients were divided into 3A or 3B according to absence or presence of deep feeders [5, 14]; unfavorable results (mRS > 2) were observed in 4 % of cases in grade 3A, 10 % of cases in grade 3B, 19 % of cases in grade 4 and 24 % of cases in grade 5 (with one death in this group). Deep feeders accounted for a significantly worse ($p = 0.01$) outcome (mRS ≥ 3 in 18 % of cases, versus 3 % of cases with superficial feeders).

For the small group of patients that had undergone radiosurgery before embolization and surgery (Fig. 2), the clinical

Table 1 Reasons for surgery and radiosurgical details in patients previously submitted to radiosurgery on AVMs

Reasons for surgery	#	Average dose at periphery	Average interval from radiosurgery to surgery (years)
Scant angio changes	9 cases	22.2 Gy	7.3
Radionecrosis	7 cases[a]	22.5 Gy	9.7s
Hemorrhage from residual	4 cases	20.8 Gy	4.2s

[a]Five cases also with cyst formation

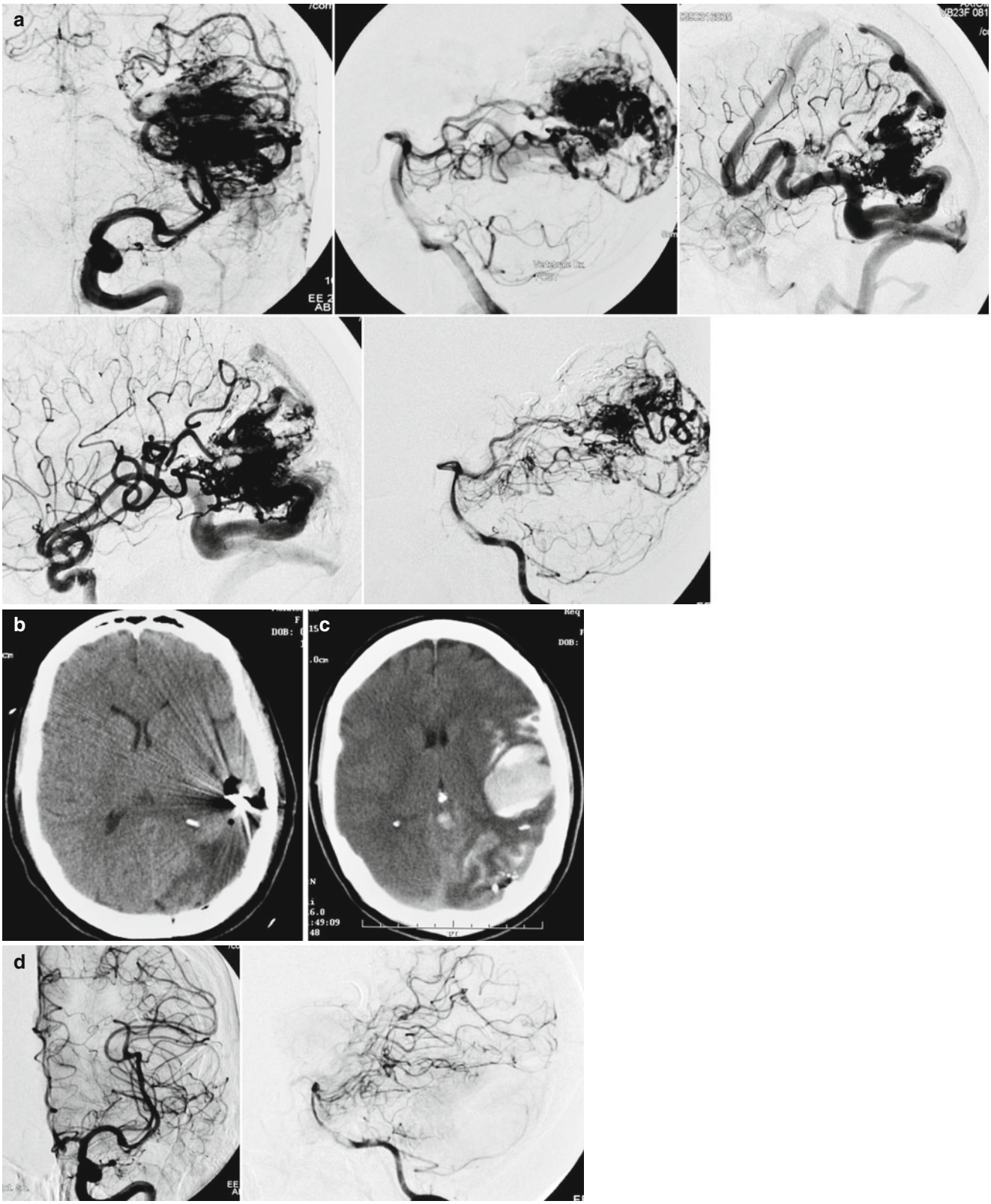

Fig. 1 A 37-year-old woman with large left temporo-occipital AVM (48 cm^3) who underwent progressive embolization; (**a**) basal angiography and angiography after embolization; (**b**) CT scan after 4th embolization, showing a large temporo-parietal hemorrhage; (**c**) post-operative CT scan; (**d**) post-operative angiography. The patient recovered progressively after surgery, showing only a partial hemianopsia after 3 months after, with normal speech

Table 2 Permanent morbidity after embolization (modified Rankin Scale)

	#	mRS 3	mRS 4
Hemorrhage months after embolization	7 cases	2 cases	1 case
Post-embolization hemorrhage	8 cases	1 case	–
Ischemic post-embolization event	5 cases	–	1 case

Table 3 Hyperemic complications in relation to AVM volume and type of feeders

	Paraventricular bleeding	Postoperative hematomas
AVM volume		
<20 cm^3 (63 cases)	6 (9 %)	5 (8 %)
>20 cm^3 (60 cases)	20 (33 %)	11 (18 %)
Significance	$p=0.001$	N.S.
AVM feeders		
Superficial only (81 cases)	7 (9 %)	6 (7 %)
Deep (42 cases)	19 (45 %)	10 (24 %)
Significance	$p<0.0001$	$p=0.01$

Table 4 Surgery-related outcome, according to Spetzler-Martin grade (grade 3B = deep feeders on angiography)

	#	mRS 2	mRS 3	mRS 4	Death
Grades 1–2	30 cases	–	–	–	–
Grade 3A	40 cases	6 (15 %)	1 (2 %)	1 (2 %)	–
Grade 3B	19 cases	4 (21 %)	2 (10 %)	–	–
Grade 4	26 cases	7 (27 %)	4 (15 %)	1 (4 %)	–
Grade 5	8 cases	4 (50 %)	1 (12 %)	–	1 (12 %)

outcome was related to AVM location and mean AVM volume for each location, and is presented in Table 5; it should be noted that in cases obtaining an mRS > 1, morbidity was due to initial hemorrhage (3 cases), or to hemorrhage months after radiosurgery (1 case).

Discussion

Preoperative embolization has been established in many centers as a complementary modality to surgery in the treatment of complex AVMs [15, 19, 24, 26, 28]; the rationale for its use is the possibility of avoiding or reducing the "so-called" hyperemic complications that frequently follow one-stage occlusion of large high-flow AVMs [1]. In a previous paper by our group – based on a group of 49 patients who underwent flow-directed embolization or selective embolization with suture threads – only a trend towards reduction of hyperemic complication was noted after embolization plus surgery, as compared to surgery alone [19]; it was speculated that these results were due to a low reduction in AVM size obtained after embolization (averaging 29–37 % in that series) and also depended upon the embolization material used.

In this group, no comparison was done between patients treated with surgery alone versus embolization plus surgery, due to the fact that all patients with AVM volumes >20 cm^3 received this combined treatment; however, the incidence of postoperative hematomas observed in the present series for AVMs >20 cm^3 (18 %) is well below the incidence of 40 % reported in 1991 [19]. We believe that the introduction of new agents – especially Onyx – has led to a better reduction of AVM size; in particular, Onyx is more diffusible than acrylic glue and allows a deeper penetration into the nidus, with an embolization that is more stable in time. This characteristic of Onyx seems to avoid (or reduce) the development of a collateral circulation, which was often observed with other materials and contributed (in the past) to the relatively scant efficacy of preoperative embolization.

Development of collateral circulation also depends upon the amount of time between each embolization (or between embolization and surgery). We are convinced that a shorter interval avoids this danger, although in our experience, logistic factors are often an obstacle to a shortening of the waiting period, so every effort should be made to wait no longer than 30 days between each embolization, and no longer than 2 weeks from the last embolization to surgery. In the few cases where surgery took place shortly after embolization – for example, in patients with hematomas caused by AVM rupture during embolization – no unusual trend towards hyperemic complications was observed, and it is possible that surgery is safe already 5–7 days after embolization.

Another reason to use preoperative embolization is supported by facilitation in AVM retraction and dissection during surgery. Although this goal is not always achieved with acrylic glue, it is certainly achieved with Onyx [15]; consequently, not only the surgical procedure is made shorter with this material, but also damage to the surrounding brain is minimized.

One of the drawbacks of Onyx is, unfortunately, an increased risk of hemorrhage reported after embolization with this agent in some groups [10–12, 20, 21, 27, 29]. We believe that this complication can be avoided if the obliteration of the AVM is not pursued aggressively; in other words, a similar reduction in AVM size can be obtained with less risk by two separate procedures than by one only. Considering this and other factors, embolization with Onyx or acrylic glue still remains a procedure that entails an additional risk (a 4.5 % complication in our group) in patients who will face surgery later on [8, 9, 26].

Regarding the influence of deep feeders on post-operative complications and outcome – already stressed by other authors [5, 14, 18] and confirmed in the present study – the small caliber of these vessels remains an obstacle to occlusion by embolization; in some cases, it is even possible

that the reduction of a part of the AVM with embolization – generally the external one – shifts the shunt flow towards the deep portion of the AVM, with difficulty controlling these fragile vessels at surgery; in these complex AVMs with deep (perforator) supply, an alternative theoretical possibility could consist of selective occlusion of perforators with radiosurgery before surgery. Indeed, in many cases operated after radiosurgery, the flow through these vessels was reduced, and no problems were faced in their cauterization with bipolar forceps.

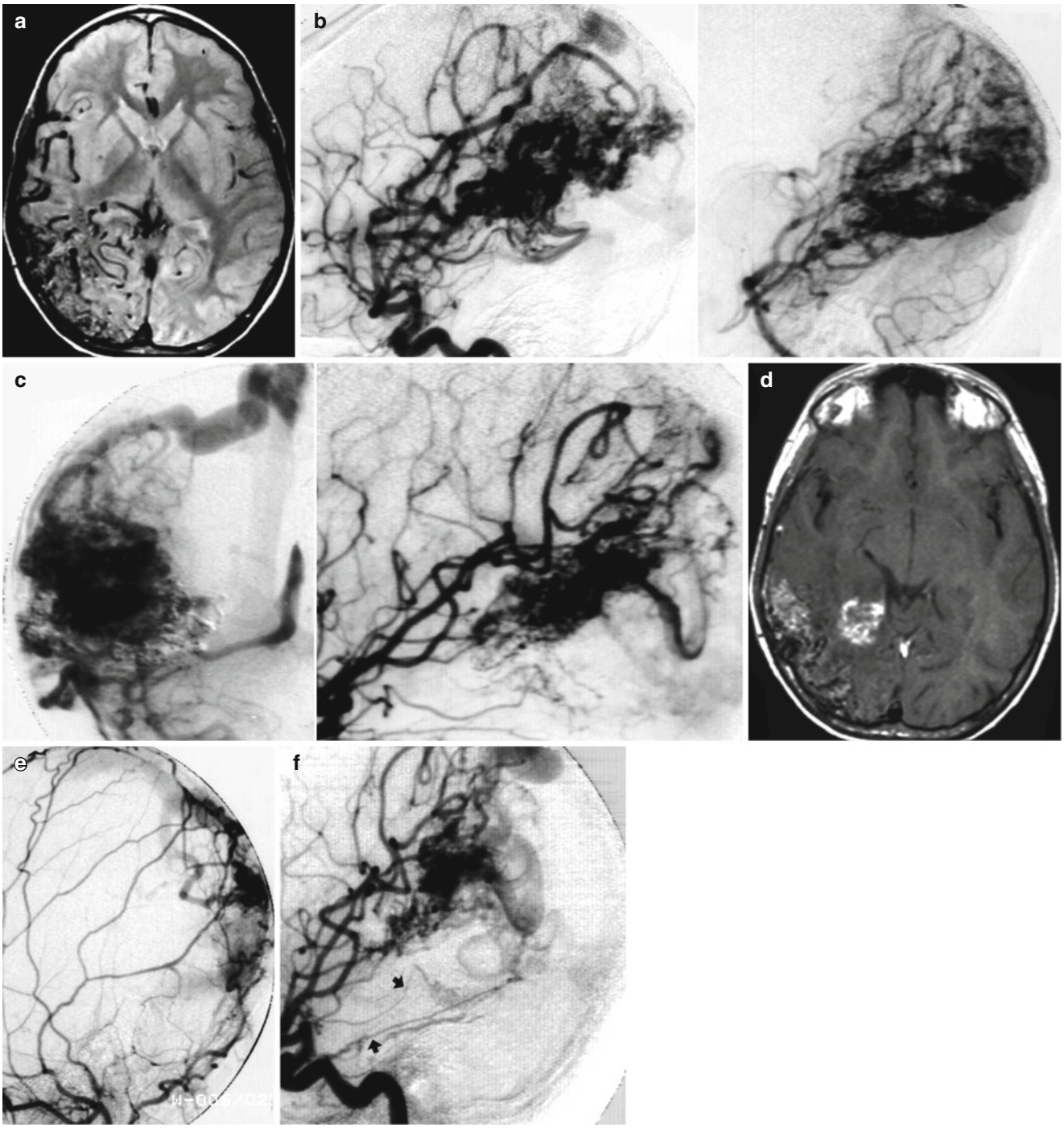

Fig. 2 A 17-year-old girl with a right temporo-parietal AVM (47 cm^3) (**a**) T2-weighted MR axial image of the AVM; (**b**) pre-embolization angiography; (**c**) angiographic changes after progressive embolizations; (**d**) T1-weighted MR axial image showing radiation changes 2 years after radiosurgery; (**e**) angiographic images 2 years after radiosurgery showing development of extensive dural supply, and (**f**) tentorial and choroidal feeders (*see arrows*); (**g**) post-operative angiography; (**h**) post-operative CT-scan. The patient showed only hemianopsia at a 6-month follow-up

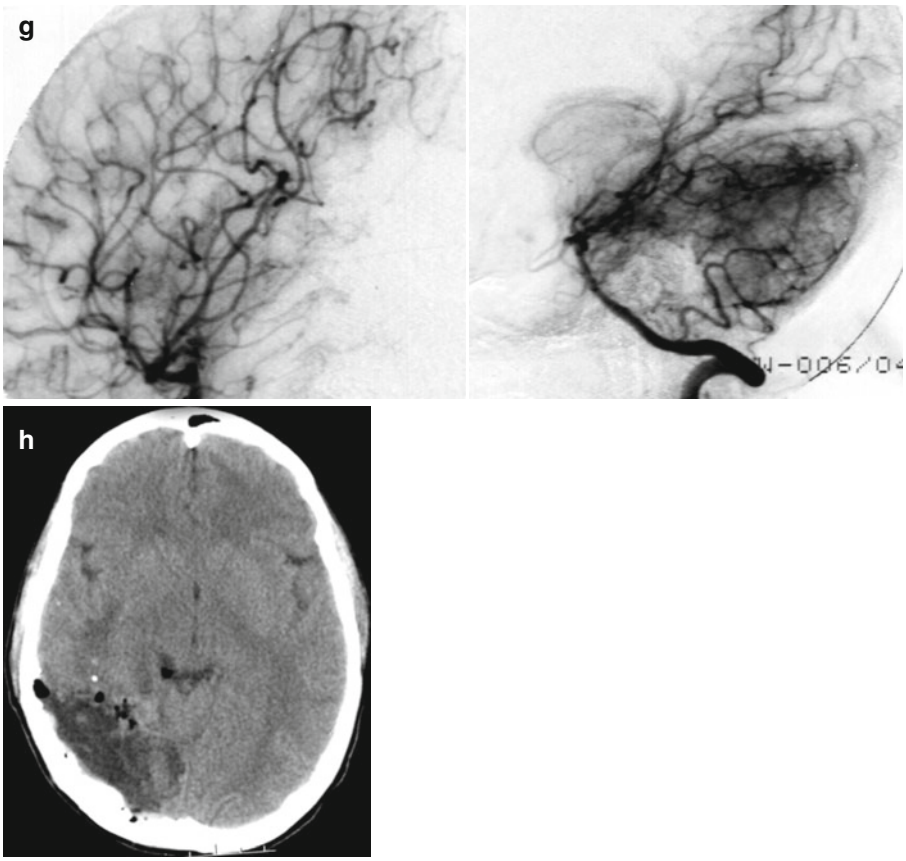

Fig. 2 (continued)

Table 5 Surgery-related outcome (only mRS ≥ 1) after embolization and radiosurgery, according to AVM location and mean AVM volume

AVM location	#	Mean AVM volume (cm^3)	Outcome (mRS > 1)
Rolandic and peri-rolandic	4 cases	31.2	1 (mRS 3)[a]
Temporal	4 cases	27.7	–
Speech area	4 cases	11.5	1 (mRS 2)[b]
Frontal: fronto-insular, fronto-callosal	3 cases	39.6	1 (mRS 2)[a]
Parasplenial	2 cases	24.5	1 (mRS 2)[a]
Posterior parietal	1 cases	16	–
Cerebellar	1 cases	30	–

[a]Due to hemorrhage months after surgery
[b]Pre-existing deficit from initial hemorrhage

In the smaller group (19 cases) treated with the three modalities (radiosurgery plus embolization plus surgery), very satisfactory results were achieved in spite of large volumes (>20 cm^3) and high Spetzler and Martin grades; this is also the experience of Steinberg and Coll, with a large group of patients undergoing this triple treatment [4, 17]. It is undeniable that radiosurgery facilitates surgical removal of the AVM, not only reducing the flow to the deep portion of the AVM (as pointed before), but also creating an avascular space between the nidus and the surrounding tissue, thus facilitating dissection of the AVM. It is not the aim of this paper to discuss the possible complications (and the etiology of complications) following radiosurgery of complex AVMs, in particular the possibility of radiation necrosis and cyst formation [6, 7]; in this regard, it should be stressed that surgery constitutes a definitive solution for patients with radiation necrosis, as already stressed by others [7, 17] and also observed in the present clinical group.

Conclusion

Embolization with acrylic glue, and especially Onyx, followed by microsurgical removal, constitutes a reasonable modality of treatment for large or critical cerebral AVMs,

with acceptable morbidity also for Spetzler and Martin grades 4–5. The adoption of a "triple" therapy – i.e., a combined treatment with embolization and surgery for complex AVMs previously treated with radiosurgery – may further improve these results.

Conflict of Interest We declare that we have no conflict of interest.

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Epilepsy and Headache After Resection of Cerebral Arteriovenous Malformations

Hans-Jakob Steiger, Nima Etminan, and Daniel Hänggi

Abstract The therapeutic benefits of microsurgery for cerebral arteriovenous malformations (AVM) with regard to headache and epilepsy are not well known. The objective of the present review is to discuss the available evidence and our own experience, which showed that two-thirds of the patients with preoperative epilepsy experienced long-term improvement, one-sixth no significant change, and an equal number worsening. New seizures occurred postoperatively in 18 % of the patients presenting with hemorrhage. Regarding headache, 40 % of patients with preoperative chronic headache reported improvement and 50 % described no change, whereas 10 % suffered from deterioration. With regard to epilepsy, the available literature suggests, that an epileptological approach with preoperative identification of the seizure focus and corresponding resection might improve the results. With regard to headache outcome, almost no information is available in the literature, suggesting that these complaints of the patients have so far not received the necessary attention. In conclusion, the long-term treatment results regarding chronic epilepsy and chronic headache need further study and optimization.

Keywords Cerebral arteriovenous malformation • Quality of life • Epilepsy • Headache

H.-J. Steiger, MD (✉) • N. Etminan, MD • D. Hänggi, MD
Department of Neurosurgery, Heinrich-Heine-Universität, Moorenstr. 5, Geb. 13.71, Düsseldorf D-40225, Germany
e-mail: steiger@uni-duesseldorf.de

Introduction

The therapeutic benefits of microsurgery for cerebral arteriovenous malformations (AVM) with regard to quality of life, headache and epilepsy are largely unknown [11]. Therefore, we tried to deduct some information from a homogenously managed population of 110 surgically treated patients with cerebral AVM who were operated on between November 1994 and June 2009. The details of the entire analysis, including quality of life, will be published elsewhere. The purpose of the actual presentation is to discuss the available literature in the light of our retrospective data and estimate of the real long-term benefit of surgery for epilepsy and headache associated with ruptured and unruptured AVM.

Data Derived from Our Own Experience

Descriptive data regarding epidemiological, socio-demographic and disease-related characteristics were extracted from the patient records. In the beginning of 2010 an attempt was made to contact all patients for a long-term follow-up with respect to epilepsy, neurological deficits, headaches, and, in particular, quality of life. The contacts were made by telephone and the information was gathered using a structured telephone interview. Information on epilepsy and headache prior to surgery was based on the information in the hospital records and not on the patients' perspective at the time of follow-up. Exploratory statistics correlated the postoperative outcome data to potential influencing factors by univariate comparison. T-statistics were used to compare mean values of stratified groups and Fisher's exact test for proportions.

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Long-term follow-up data were available in approximately half of the treated patients. The average interval between AVM treatment and follow-up interview was 7 years. The profile of the sample available for follow-up corresponded well to the overall patient population with regard to initial neurological deficits and at the time of discharge, Spetzler-Martin grade, hemorrhagic manifestation etc., thereby excluding a significant selection bias in the sample available for the quality of life survey. Only the group with a reduced level of consciousness at the time of discharge was underrepresented in the cohort available for follow-up. Two-thirds of the patients were admitted after hemorrhage.

Preoperatively, 36 % of all patients had experienced at least one epileptic seizure and 25 % suffered of chronic headaches. At the time of the follow-up after an average of 7 years, 65 % of the follow-up cohort reported improvement of epilepsy (Engel class 1–2, free of disabling seizures or rare disabling seizures), 17 % reported no significant change and 18 % reported worsening. Another 18 % of patients in whom epilepsy was not known at the time of AVM treatment reported seizures during follow-up. All but one of these had been treated for their AVM after hemorrhage.

Regarding headache, 26 % of patients reported chronic headache at the time of admission. Upon long-term follow-up 39 % of these patients reported improvement, 54 % no change and 8 % worsening.

Review of the Literature

The effect of AVM treatment on epilepsy and headaches is an important unclarified issue in AVMs with these leading symptoms. A positive effect has been reported after radiosurgery [2, 3, 6, 10, 12]. Regarding microsurgery, Heros and colleagues reported that of the patients who did not have seizures before surgery, 8.2 % had only one or two seizures during the immediate postoperative period, and 7.1 % had late seizures that were well controlled with medication in all. Of the patients who had seizures before surgery, over half were either cured or greatly improved with respect to the seizures [5]. Hoh and colleagues reported seizure outcome in 141 epileptogenic AVMs following multimodal treatment, as determined by the Engel Seizure Outcome Scale [6]. There were 66 % Class I (free of disabling seizures), 10 % Class II (rare disabling seizures), 0.9 % Class III (worthwhile improvement), and 20 % Class IV (no worthwhile improvement) outcomes. The results of our poll provided comparable data in that 65 % of the patients with preoperative epilepsy reported improvement (Engel class 1–2, free of disabling seizures or rare disabling seizures), 3 (16.7 %) reported no significant change, and 3 (17.6 %) reported worsening.

Yeh and coworkers reported their experience with an epilepsy surgery approach to epileptogenic AVM [13]. All patients underwent preoperative electroencephalography and intraoperative electrocorticography, and total excision of the AVM. Additional cortical excision was performed in 25 cases and they also found remote seizure foci in the ipsilateral mesial temporal or frontal structures in 20 % of their patients. Postoperative seizure control during a follow-up study of 5 years on average were excellent, in 70 % (Engel Class I) and good (Engel Class II) in another 20 %. The results appeared to correlate with age at seizure onset, duration of seizures, location of lesions, and cortical excision. Patients with seizure onset after the age of 30 had better results as well as patients with a seizure history of less than 1 year. The authors concluded that a differentiated approach to epileptogenic AVM, including cortical excision in selected patients, can improve seizure control and the importance of early surgery of a cerebral AVM in young patients presenting with epilepsy is emphasized.

Piepgras and colleagues reported their results in a series of 280 cases of cerebral arteriovenous malformations [9]. Follow-up evaluation, after a mean of 7.5 years, was accomplished through re-examinations, telephone interviews, and written questionnaires. Overall, 90 % of the surviving patients with a follow-up period of more than 2 years were free of seizures at their last examinations. Of the 280 patients in this group, 163 had experienced no seizures preoperatively. Of these, only 6 % were having new ongoing seizures. The 2-year minimum follow-up study in 110 of the 117 patients with preoperative seizures revealed that 83 % were seizure-free (with 48 % no longer receiving anticonvulsant therapy), while 17 % still suffered intermittent seizures.

Hyun and colleagues recently reported their experience with the multidisciplinary treatment of 399 patients including surgical resection, radiosurgery, and embolization, either alone or in combination [7]. The median follow-up period was 6.0 years. Of their patients, 21.5 % experienced seizures before treatment. After treatment, 70 % of these patients were seizure-free. The authors also compared the results between the treatment modalities. Seizure-free outcomes 1 year after microsurgery, radiosurgery, or embolization were 78, 66, and 50 %, respectively. They concluded that microsurgery led to the highest percentage of seizure-free outcomes.

The situation with regard to headaches following treatment is comparable to epilepsy. A few papers on radiosurgical treatment results suggest improvement in patients with headache as the presenting symptom [1, 4, 8]. In addition, some information with regard to multimodal therapy is available. Dehdashti and colleagues reported that in occipital AVMs with headache as the presenting symptom, 83 % improved after multimodal therapy, in contrast to only 30 % who improved under observation [1]. In our analysis

including not only occipital AVMs, the results were somewhat less positive: 39 % of patients with preoperative chronic headache reported improvement, 54 % no change and 8 % deterioration.

Conclusion

The data on the effect of microsurgery and embolization for the control of epilepsy and headache are still scarce. Our results suggest that an epileptological approach to epileptogenic AVM, as suggested by Yeh et al. might be worthwhile. Further prospective data acquisition is a mandatory precondition in order to indicate microsurgery for patients with unruptured AVM presenting with epilepsy and/or headache.

Conflict of Interest We declare that we have no conflict of interest.

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Results of Surgery for Cavernomas in Critical Supratentorial Areas

A. Pasqualin, P. Meneghelli, A. Giammarusti, and S. Turazzi

Abstract A total of 121 patients surgically treated between 1991 and 2011 for cavernomas in critical supratentorial areas were evaluated. Anatomical location, size and the possible association with developmental venous anomalies (DVA) were assessed in each case: 43 cavernomas were in the speech area, 39 were rolandic (or peri-rolandic), 14 insular, 10 nuclear, 9 calcarine and 6 ventricular. In 49 % of the cases, the cavernoma was <1.5 cm; in 6 patients, radiological growth was documented. A method of intraoperative localization was adopted in 78 cases: B-mode echography or a stereotactic guide in 22 cases, and a neuronavigation system in 56 cases; preoperative angiography was done in 22 cases. Early postoperative epilepsy (within 7 days of surgery) was observed in 15 cases. As for clinical outcome, 14 patients presented with mild symptoms (modified Rankin Scale 1–2); significant deficits occurred *ex-novo* in 5 patients. The presence of epilepsy at follow-up was assessed through the Maraire Scale: 44 % of patients presenting with epilepsy were free of seizures and without therapy at a mean follow-up of 4.6 years, and an additional 55 % had complete control of seizures with therapy. It is concluded that surgery is indicated in the management of cavernomas in critical supratentorial locations, with a caveat for insula and especially basal ganglia.

Keywords Critical supratentorial cavernomas • Neuronavigation • Intra-operative echography • Microsurgery • Epilepsy • Venous anomaly

A. Pasqualin (✉) • P. Meneghelli • A. Giammarusti
Section of Vascular Neurosurgery, Institute of Neurosurgery, Verona City Hospital, Via Milazzo, 2, Verona 37128, Italy
e-mail: albertopasqualin@tin.it

S. Turazzi
Institute of Neurosurgery, Verona City Hospital, Via Milazzo, 2, Verona 37128, Italy

Introduction

Supratentorial cavernomas represent 76 % of all central nervous system cavernomas; clinical management of supratentorial cavernomas, especially in critical areas, is still under discussion [1, 2, 10]. Critical supratentorial cavernomas are characterized by their location inside an eloquent area or inside an area that needs, for surgical approach, the passage throughout an eloquent area [4, 8, 22]. For these lesions, the risk of bleeding – possibly leading to intraparenchymal hematoma formation is eliminated with surgery, but post-operative morbidity is not negligible, and the efficacy of surgery in elimination of epilepsy is still not proven.

The aim of this paper is to review our experience in managing critical supratentorial cavernomas, with particular consideration to location-related outcome and long-term control of epilepsy.

Material and Methods

Of 407 patients undergoing surgery for cerebral cavernomas between 1991 and 2011, 121 were operated on in critical supratentorial areas and constitute the substance of this study; 43 patients (35 %) were operated on in the speech cortex, 39 patients (32 %) in the rolandic (and peri-rolandic) cortex, 9 (7 %) in the visual cortex, 14 (11 %) in the insula, 10 (8 %) in the basal ganglia, and 6 (5 %) in the ventricles (mainly in 3rd ventricle).

There were 65 females (54 %) and 56 males (46 %); mean age at surgery was 30.9 years (range 5–69 years). Clinical presentation consisted of epilepsy in 77 cases (64 %), hemorrhage in 35 cases (29 %) (with significant hematoma reported in 15 patients, and multiple hemorrhages in 4 patients) and neurological deficits in 10 cases (8 %); in 8

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cases (6 %) the cavernoma was discovered incidentally. All patients were assessed with magnetic resonance imaging (MRI) and in 22 cases also with angiography; in order to define the diameter of the lesions, the possible presence of multiple lesions, developmental venous anomalies (DVA) or other cerebro-vascular malformations, and evidence of progressive radiological growth [21]. In 59 patients (49 %) the diameter of the lesion was <1.5 cm; in 10 patients (8 %) multiple cavernomas were observed; in 12 patients (10 %) significant DVAs were present; in 1 case an arterio-venous malformation was already present before the development of the cavernoma (thus representing a "de novo" appearance of a cavernoma) [21].

The first step in surgical planning was localization of the lesion: in our group, B-mode echography was applied in 19 cases, Leksell stereotactic guide in 3 cases and a neuronavigating system (Medtronic Stealth Station Treon) in 56 cases; as mentioned above, pre-operative angiography was done in 22 cases in order to confirm the diagnosis of DVA and to better define its morphology. More recently, functional MRI (fMRI) and diffusion tensor imaging (DTI) were introduced in pre-operative planning, in order to recognize speech and motor areas (fMRI) and to map the pyramidal tract (DTI). The surgical approach was chosen in order to avoid or decrease peri-operative morbidity: (1) a trans-sulcal approach was chosen for subcortical lobar cavernomas; (2) a trans-sylvian approach for insular and basal ganglia cavernomas and for most cavernomas in the speech area; (3) a pterional approach for 2 caudate cavernomas; (4) an interhemispheric approach in 7 cases (anterior interhemispheric for 1 cingular and 3 ventricular cavernomas and posterior interhemispheric for 1 thalamic and 2 calcarine cavernomas); and (5) a trans-trigonal (ventricular) approach for a thalamic cavernoma.

Among postoperative complications, early epilepsy (within 7 days of surgery) was evaluated in detail.

One or more clinical evaluations were performed at follow-up, ranging from 6 months to 20 years (mean follow-up 4.7 years). Clinical outcome was assessed through the modified Rankin Scale (mRS); neurological deficits were divided in transient deficits – lasting for <1 month, 1–3 months and >3 months – and permanent deficits, divided in mild (mRS 1–2) and significant (mRS > 3). Cavernoma location (divided in superficial versus deep) was related to outcome and to early post-operative seizures. Post-operative epilepsy was classified according to the Maraire scale: grade I – no seizures, no antiepileptic drugs (AEDs); grade II – no seizures with AEDs; grade III – sporadic seizures with AEDs; grade IV – disabling epilepsy. Statistical evaluation was done through the chi-square test.

Results

Following surgery, 2 patients (1.6 %) presented with significant extradural hematomas, and 7 patients (5.7 %) experienced hemorrhagic complications that did not require evacuation; 1 patient (0.5 %) experienced a post-operative ventriculitis and was treated with placement of an external ventricular drainage (EVD) in order to perform systemic and intra-thecal antibiotic therapy; 1 patient (0.5 %) developed a post-operative ventricular cyst that needed stereotactic drainage later on.

Early post-operative epilepsy was reported in 7 of the 39 cases operated on in the rolandic or perirolandic cortex, in 5 of 43 operated on in the speech cortex, in 2 of 14 operated on in the insula, and 1 case out of 9 operated on in the visual cortex (Table 1).

Surgery-related outcome is presented in Tables 2 and 3. As for superficial cavernomas (Fig. 1) (Table 2), 21 cases out of 39 (54 %) operated in the rolandic/perirolandic cortex showed post-operative neurological deficits: in 16 patients the deficit disappeared within 6 months; 5 patients (13 %) developed permanent deficits, 3 of them with a mild disability (mRS 1–2) and 2 with a significant disability (mRS > 3) (as a consequence of previous hemorrhage in one). Only transient deficits were reported in 14 patients operated on in the speech area, mostly lasting for less than 1 month (64 %). After surgery in the visual cortex, in 4 cases (55.5 %) a visual deficit was present transiently and in only one case it was permanent (quadrantopsia).

As for deep cavernomas (Table 3), 9 of the 14 patients operated on in the insula (Fig. 2) showed post-operative deficits that were transient in 5 cases (55 %) and permanent in 4 cases, with significant disability (mRS > 3) in 2 patients (22 %). As for intraventricular cavernomas (Fig. 3), 3 cases (50 %) out of 6 patients showed post-operative deficits (2 permanent but not disabling). As for basal ganglia cavernomas, 9 patients (90 %) showed neurological deficits that were transient in 1 case (disappearing within 30 h), mild (mRS 1–2) in 6 cases and disabling (mRS > 3) in 2 cases. Statistically, surgery for superficial lesions carried a lower risk of post-operative deficits as compared to deep lesions ($p = 0.02$), with a

Table 1 Early post-operative seizures and cavernoma location

Cavernoma location	#	%
Rolandic (39 cases)	7	38
Speech (43 cases)	5	12
Insular (14 cases)	2	14
Visual (9 cases)	1	11

Table 2 Clinical outcome in patients with cavernomas in a superficial location

	Transient deficits			Permanent deficits	
	<1 month	1–3 months	>3 months	Mild (mRS 1–2)	Significant (mRS ≥ 3)
Rolandic (39 cases)	6 (15 %)	4 (10 %)	6 (15 %)	3 (8 %)	2[a] (5 %)
Speech (43 cases)	9 (21 %)	4 (9 %)	1 (2 %)	–	–
Visual (9 cases)	1 (11 %)	1 (11 %)	2 (22 %)	1 (11 %)	–

[a]One case due to previous hemorrhage

Table 3 Clinical outcome in patients with cavernomas in a deep location

	Transient deficits			Permanent deficits	
	<1 month	1–3 months	>3 months	Mild (mRS 1–2)	Significant (mRS ≥ 3)
Insular (14 cases)	1 (7 %)	2 (21 %)	1 (7 %)	2 (14 %)	2 (14 %)
Ventricular (6 cases)	1 (17 %)	–	–	2 (33 %)	–
Basal ganglia (10 cases)	–	1 (10 %)	–	6 (60 %)	2 (20 %)

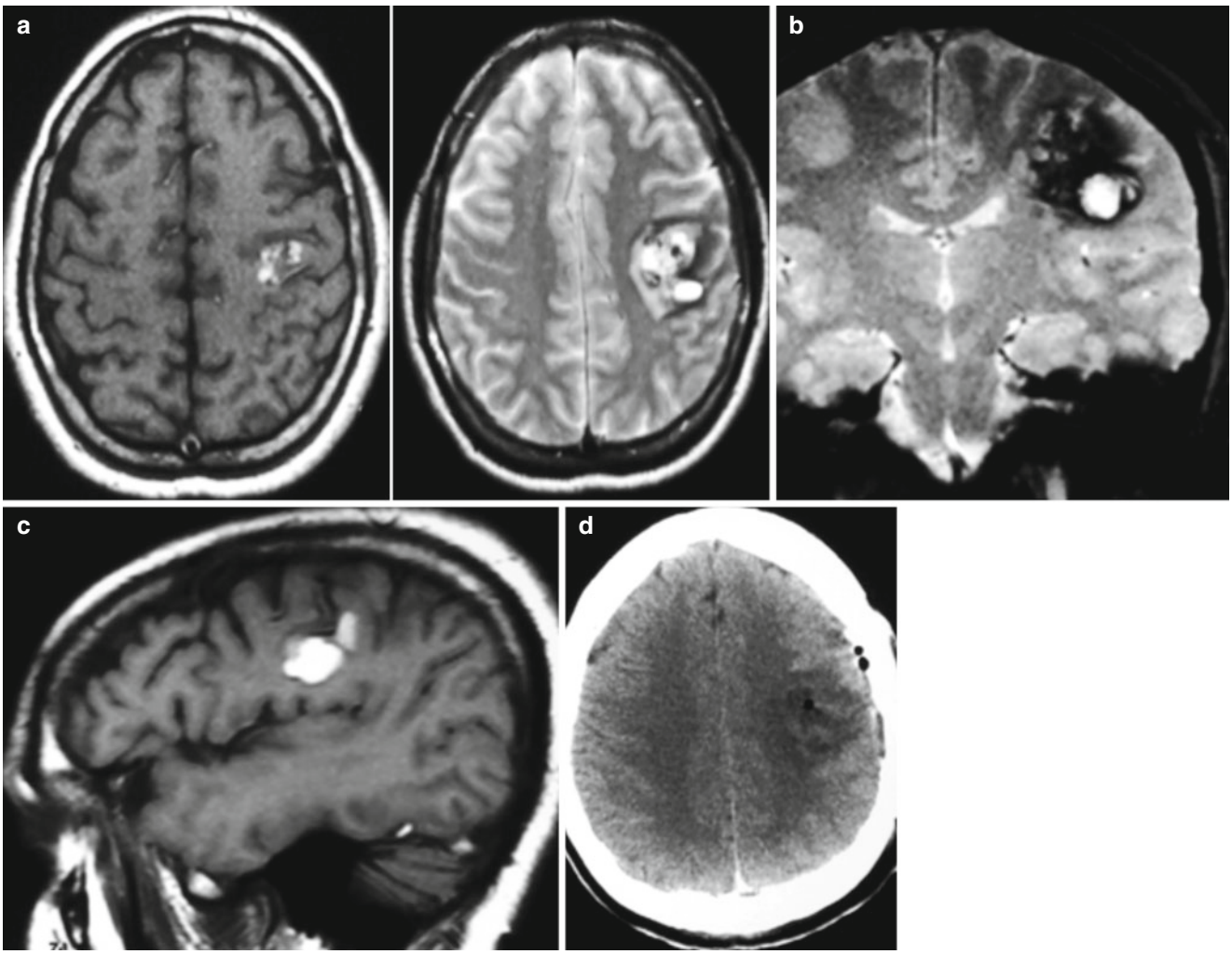

Fig. 1 A 31-year-old man with hemorrhage and left subcortical rolandic cavernoma; (**a**–**c**) axial, coronal and sagittal view in T1 and T2 weighted MRI sequences; (**d**) post-operative CT-scan. The patient experienced a transient hemiparesis

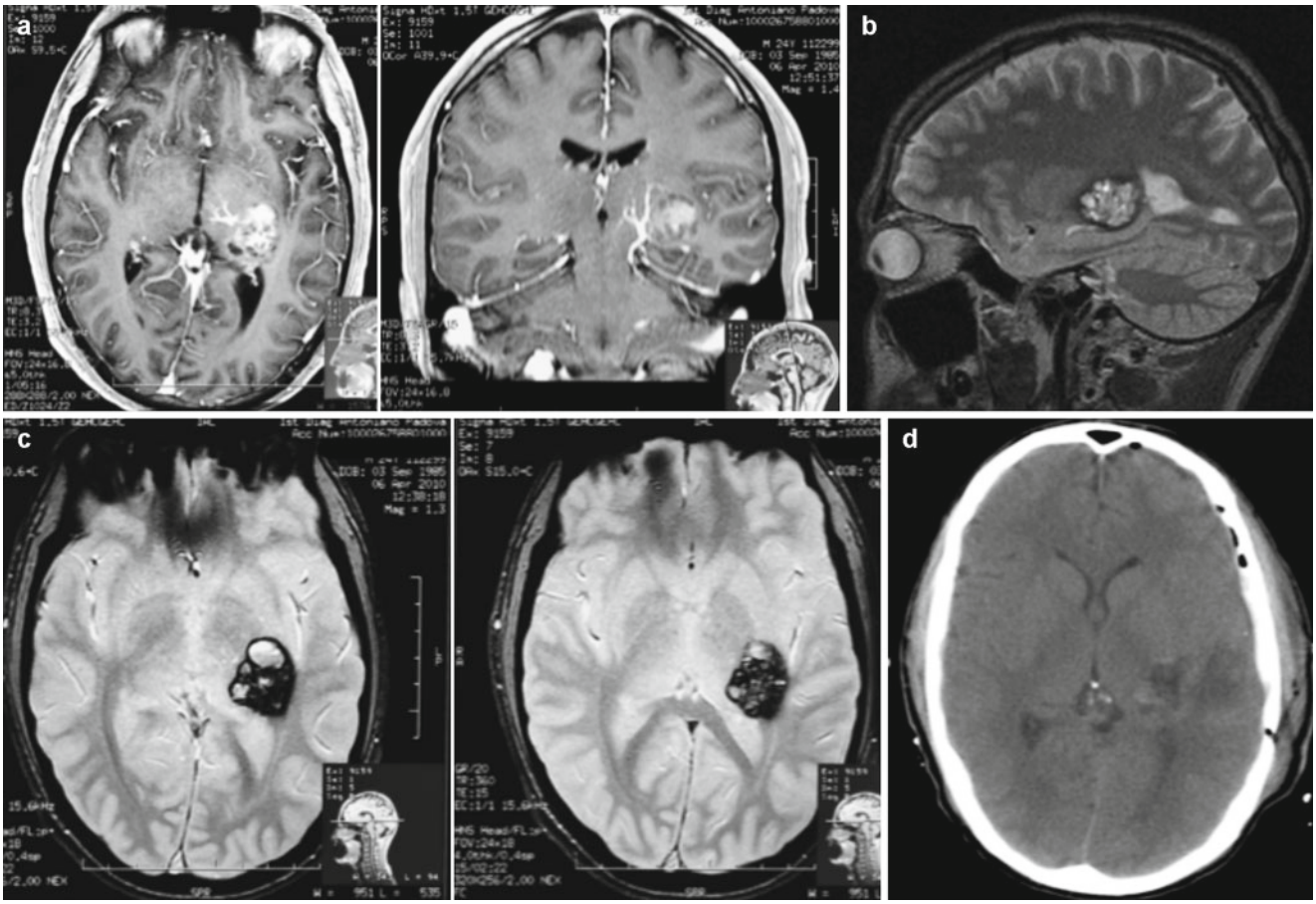

Fig. 2 A 24-year-old man with headache and left posterior insular cavernoma; (**a**) axial and coronal T1 weighted + Gadolinium MR images, with evidence of a venous anomaly medial to the cavernoma; (**b**) sagittal view in T2 weighted MR images; (**c**) axial view in fast spin-echo T2 MR images; (**d**) post-operative CT-scan. The patient experienced a transient dysphasia, with complete recovery 1 month after surgery

highly significant difference in the incidence of permanent deficits ($p<0.0001$).

Epilepsy at follow-up is presented in Table 4, according to the Maraire scale [16]; as a whole, favorable results (Maraire 0) were observed in 44 % of cases, with no seizures and no therapy at follow-up. Moreover, of 15 patients with early post-operative seizures, 13 were seizure-free without therapy at follow-up.

Discussion

Surgery for cavernomas in critical supratentorial areas remains a matter of controversy [1, 2, 11–14, 23]; while an operative procedure appears reasonable in the presence of epilepsy, a previous hemorrhage (especially if significant) or a neurological deficit, it remains questionable for an incidental discovery; the low incidence (8 %) of cavernomas incidentally discovered in our surgical series proves this point. However, it is our belief – and it is also the reason for carrying out this study – that a detailed assessment of outcome may lead to a widening of the surgical indications whenever morbidity remains mainly transient, i.e., in superficial critical areas (with only 5 % of significant deficits in the rolandic area in our series). This figure has to be compared to the risk of hemorrhage if the cavernoma is left untreated, which is reported around 1 % per year or less [18, 20]; more recently, Flemming et al., have stated that the risk of hemorrhage depends on clinical presentation, being higher (6 % per year) for patients with previous hemorrhage [7].

If the cavernoma is located in deep critical areas – especially in the insula or in the basal ganglia – postoperative morbidity becomes significant (mRS > 2 in 14 % of insular cavernomas and in 20 % of basal ganglia cavernomas in our series) and an operative procedure can be recommended only in the presence of consistent symptomatology; in these locations, surgery should be performed through a wide opening of the sylvian fissure, determination of the pyramidal tract on preoperative MRI [19], calculation of the shortest (and least dangerous) way to the outer surface of the lesion, accurate skeletonization of arterial branches adjacent (or adhering) to the cavernoma, and paying particular attention to avoid thermal injury by limiting the use of bipolar coagulation as much

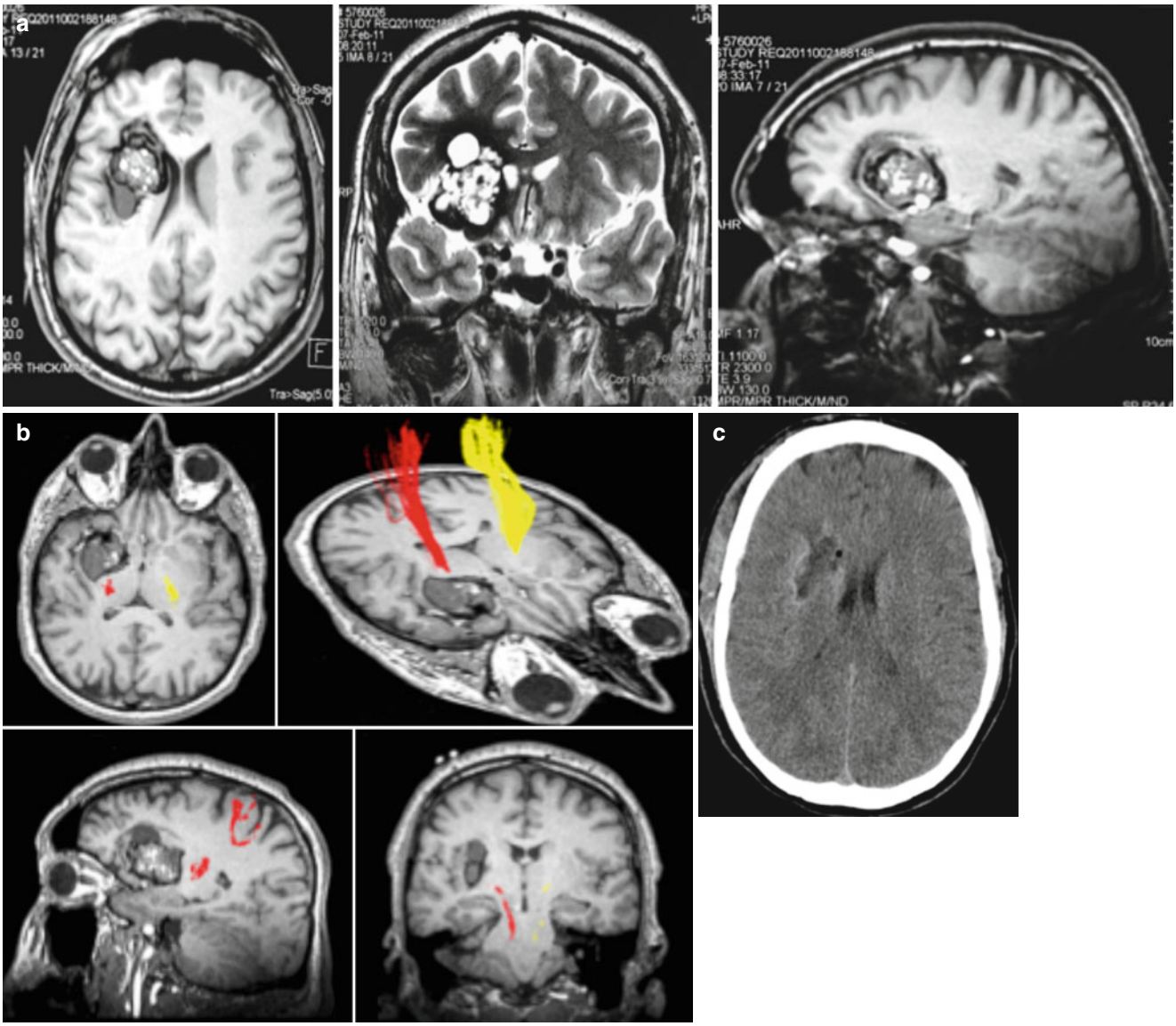

Fig. 3 A 35-year-old man with epilepsy and large right fronto-insulo-caudate cavernoma (with adjacent cystic component); (**a**) axial, coronal, sagittal view in T2 weighted MR images; (**b**) reconstruction of the pyramidal tract (DTI); (**c**) post-operative CT-scan. The patient experienced a transient left hemiparesis (<30 h) and exhibited no deficits at discharge

Table 4 Epilepsy at follow-up, in 77 patients presenting with epilepsy

Location	Maraire grade			
	0	1	2	3
Rolandic (34 cases)	10 (29 %)	23 (68 %)	1 (3 %)	–
Speech (28 cases)	16 (57 %)	12 (43 %)	–	–
Visual (3 cases)	1 (33 %)	2 (67 %)	–	–
Insular (7 cases)	4 (57 %)	3 (43 %)	–	–
Basal ganglia (5 cases)	3 (60 %)	2 (40 %)	–	–
Total (77 cases)	34 (44 %)	42 (55 %)	1 (1 %)	–

as possible, and by using continuous irrigation and tamponade of bleeding points with cottonoids. Moreover, intraoperative monitoring can be useful in the approach to these lesions [27]. With these precautions, permanent surgical morbidity for these dangerous locations has decreased in our series in the last years, and is now comparable to the results reported by other authors (from 5 to 11 % for surgery of cavernomas in the basal ganglia, according to Steinberg and Chang) [4, 22]. For cavernomas in the thalamic area, an alternative surgical approach is constituted by the transtrigonal (ventricular) route; although the surgical trajectory is longer, there is decreased risk of motor (or sensory) deficits than through the sylvian route, but there may be an increased risk of CSF-linked complications.

The need for a precise method of intraoperative localization cannot be overemphasized, considering that even cavernomas in lobar areas have a subcortical location and are unrecognizable on the surface of the brain; although other

methods of localization can be used (such as intraoperative echography or a stereotactic guide) [9, 15, 24, 25, 27], a neuro-navigating system remains an accepted standard [8, 24, 26, 27], with a caveat for changes induced by loss of cerebro-spinal fluid during surgery; in this regard, the recent introduction of intraoperative MRI [3, 8] should allow a more precise anatomical localization throughout the entire procedure.

The presence of associated venous anomalies remains a risk in surgery of critical supratentorial cavernomas. In these cases, the operative approach should be planned with the aim to respect the venous branches adhering (or adjacent) to the cavernoma in order to avoid venous ischemia or infarction; gadolinium-enhanced MRI or even angiography may be indicated to better document the precise course of the venous anomaly.

The efficacy of surgery in eliminating (or reducing) epilepsy in patients with supratentorial cavernomas is still under debate [5, 6, 8, 17, 27]. Some authors reported that up to 40 % of patients presenting with epilepsy and harboring a cavernoma not submitted to surgery proceed towards a severe form of epilepsy that barely responds to drugs [5, 17]. If this figure is true, our results should be considered satisfactory since almost half of our patients are seizure-free without antiepileptic drugs at long-term follow-up; it is even possible that a larger percentage of patients is cured of epilepsy, since in many cases therapy is continued by the patient despite the long-term disappearence of seizures. Moreover, the possibility of early post-operative seizures – occurring mainly for the rolandic location in our series – does not account for an increased risk of epilepsy at long-term follow-up.

Conclusion

The microsurgical excision of cavernomas in critical supratentorial areas is linked with satisfactory results if the lesion is superficially located, suggesting a widening of operative indications even for the rolandic area. For insular and especially basal ganglia cavernomas, surgery is risky and the operative indications must be balanced carefully in each case; the application of some technical precautions may enhance the safety of surgery for these deep locations. The efficacy of surgery in eliminating epilepsy in a high percentage of patients with critical cavernomas must also be taken into account when deciding the best management of these lesions.

Conflict of Interest We declare that we have no conflict of interest.

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High Resolution Imaging of Cerebral Small Vessel Disease with 7 T MRI

Susanne J. van Veluw, Jaco J.M. Zwanenburg, Jeroen Hendrikse, Anja G. van der Kolk, Peter R. Luijten, and Geert Jan Biessels

Abstract Small vessel disease (SVD) refers to all pathological processes that affect the small vessels of the brain. SVD is an important cause of acute stroke, but is also a leading cause of aging-related cognitive decline and dementia, due to more insidious brain parenchymal damage. The introduction of high field strength MRI (7 T) is likely to offer important new perspectives on the role of SVD in these disorders. In this overview we illustrate the opportunities that 7 T MRI offers in high resolution vascular imaging. In particular, we will show the capability of 7 T MRI to depict the small arteries and veins in the brain, the vascular wall of intracranial arteries, perivascular spaces, and microvascular parenchymal lesions, including microbleeds and microinfarcts.

Keywords Vasculopathy • Small vessel disease • Magnetic resonance imaging • Ultra-high field strength • Perivascular spaces • Microbleeds • Microinfarcts • Lacunes • Cerebral ischemia

Introduction

The term cerebral small vessel disease (SVD) refers to all the pathological processes that affect the small vessels of the brain, including small arteries and arterioles, but also capillaries and small veins [9, 10]. SVD is a major cause of acute stroke, but is also a leading cause of aging-related cognitive decline and dementia. Unlike large vessels, small vessels cannot currently be visualized with conventional brain imaging techniques. Therefore, the parenchymal lesions that are the consequence of SVD and can be readily detected by brain imaging, in particular with MRI, are widely accepted as the main marker of SVD and are sometimes even considered to be the equivalent of SVD [10]. These lesions include lacunar infarctions, white matter hyperintensities (WMHs), and cerebral microbleeds (CMBs). It is important to emphasize that these parenchymal lesions represent only one part of the spectrum of SVD and that we need more advanced imaging techniques to capture the burden of vascular disease in the brain more fully.

In this respect, the introduction of high field strength MRI (e.g., 7 T) is likely to offer important new perspectives. The added value of 7 T is the increased signal to noise ratio (SNR) with the ability to identify small structures with high resolution. Examples of this higher sensitivity of 7 T are the visualization of lenticulostriate arteries on time-of-flight (TOF) MR angiography images [8], the detection of the layered structure of the gray matter on T2 weighted fluid attenuated inversion recovery (FLAIR) 7 T images [13], and the improved detection of CMBs on T2* weighted images [4]. In addition to increased SNR and changes in MR contrasts at 7 T, i.e., improved contrast to noise ratios (CNR) can be exploited. Examples are the shorter T2* that allows an improved detection of CMBs and for better functional MRI signals and the longer T1 values for improved arterial spin labeling MRI perfusion signal. The combination of increased SNR and CNR can thus be exploited to visualize anatomical structures or physiological processes that are below the detection limits of MRI at lower field strength.

Of note, imaging at 7 T still has some challenges and limitations, and is currently applied primarily for research purposes. Important technical challenges are inhomogeneity in both the static magnetic field and in the RF transmit fields, which may lead to image inhomogeneity and artifacts. These challenges drive the development of new hardware, such as multi-transmit coils, which have more degrees of freedom for homogenizing the RF transmit field.

S.J. van Veluw (✉) • G.J. Biessels
Department of Neurology, Brain Center Rudolf Magnus, University Medical Center Utrecht, G03.232, 85500, Utrecht 3508 GA, The Netherlands
e-mail: s.j.veluw-2@umcutrecht.nl

J.J.M. Zwanenburg • J. Hendrikse • A.G. van der Kolk
P.R. Luijten
Department of Radiology, University Medical Center Utrecht, Utrecht, The Netherlands

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Moreover, imaging at high field strength also requires adaptation and development of new MR sequences, to obtain similar contrast as at conventional lower field strengths, taking into account the different T1 and T2 relaxation times at 7 T. Another issue is that the sequences should stay within the specific absorption rate (SAR) limits. This is more challenging at high fields, as the SAR of RF pulses increase with the increased RF frequency at high field strength. Other limitations of 7 T imaging at present arise from safety issues. Subjects with metal in or on their bodies and/or medical implants are currently not allowed to undergo scanning at this high field strength. This can create a selection bias in the inclusion of subjects regarding patient-control studies. Fortunately, with increasing experience and improving technology, many of the challenges of high field imaging can be overcome and the advantages for improved detection, clinical diagnosis, and treatment can be increasingly appreciated.

In this report we illustrate the opportunities that 7 T MRI offers in vascular imaging. In particular, we will show the capability of 7 T MRI to depict the small arteries and veins in the brain, the vascular wall of intracranial arteries, perivascular spaces, and microvascular parenchymal lesions. Although this paper focuses on the application of 7 T MRI in the context of SVD, it will be evident that several of the techniques that will be covered have much wider applications.

Blood vessels

With 7 T MR imaging, the blood vessels in the brain can nowadays be visualized non-invasively in even greater detail than before. A non-contrast enhanced MR angiography (a 3D time-of-flight (TOF) arteriogram) with voxel sizes of $0.4 \times 0.5 \times 0.6$ mm^3 shows small vessels such as the lenticulostriate arteries [8]. The development of dual echo combined TOF angiography (first echo) and susceptibility weighted imaging (SWI, second echo) with voxel sizes of $0.4 \times 0.5 \times 0.6$ mm^3 further enables depicting arteries and veins within a single acquisition. Using the maximum intensity projection of the first echo 3D TOF, arteries appear bright on the scan. A minimum intensity projection of the second echo highlights dark veins (Fig. 1).

Most vascular imaging applications are based on visualizing the lumen of blood vessels. However, many pathological processes arise in the vessel wall. With high field strength MRI, it has become possible to depict the intracranial vessel wall and its pathology with increasing detail. This has recently been demonstrated by our study group using magnetization preparation inversion recovery TSE (MPIR-TSE) at 7 T [12]. This allows the study of plaques in intracranial vessels and their role in stroke (Fig. 2).

Perivascular spaces (PVS) are extracerebral fluid filled spaces that surround brain arteries, arterioles, veins, and venules. PVS are physiological structures that are present in all individuals and course from the cortical or basal brain surface into the brain parenchyma. With conventional MRI, only the abnormal, enlarged PVS can be visualized. These enlarged PVS on conventional MRI are thought to be a correlate of SVD and are associated with dementia [5, 6]. 7 T MR imaging now allows visualization of normal, non-enlarged PVS, for example, in young adults (Fig. 2). Furthermore, by combining images of PVS and blood vessels, the relationship between these structures can now, for the first time, be assessed non-invasively. High field strength MRI is thus likely to further our understanding of (enlarged) PVS as a marker of SVD.

Parenchyma

Conventional MRI markers of SVD, including WMHs and lacunar infarctions, do not fully capture the burden of vascular brain damage in aging and dementia. In this context, microvascular lesions, in particular CMBs and cerebral microinfarcts (CMIs), are attracting increasing attention. Autopsy studies have demonstrated that these lesions are common and are clearly correlated with impaired cognition, also in patients diagnosed with Alzheimer's disease (AD) [9, 11]. Because CMIs are small (reported sizes vary between 50 μm and a few mm), they go undetected on conventional MRI [2]. The paramagnetic effects of hemosiderin allow the detection of CMBs with conventional MRI, despite limited size, but CMB detection is facilitated at higher field strength [7]. In a study done in our group by Conijn et al., it was shown that on 7 T dual echo T2* weighted images, up to three times as many CMBs could be detected, as compared to 1.5 T 3D T2* weighted images [4].

In one case report, 7 T T2* weighted images with short echo time, used for noncontrast enhanced MR angiography, revealed a direct relationship between several CMBs and a small penetrating artery in a single scan acquisition of a 42-year-old male patient who presented with acute headache, dysphasia, and severe hypertension [1]. This is another example of the high sensitivity of 7 T MRI, allowing visualization of the hemorrhages together with the related "leaking" small arteries (Fig. 3).

7 T MR imaging was recently applied in patients with early AD and healthy age-matched controls to assess CMB load. The prevalence of CMBs was higher for 7 T imaging (78 % of early AD patients had CMBs, compared to 44 % of

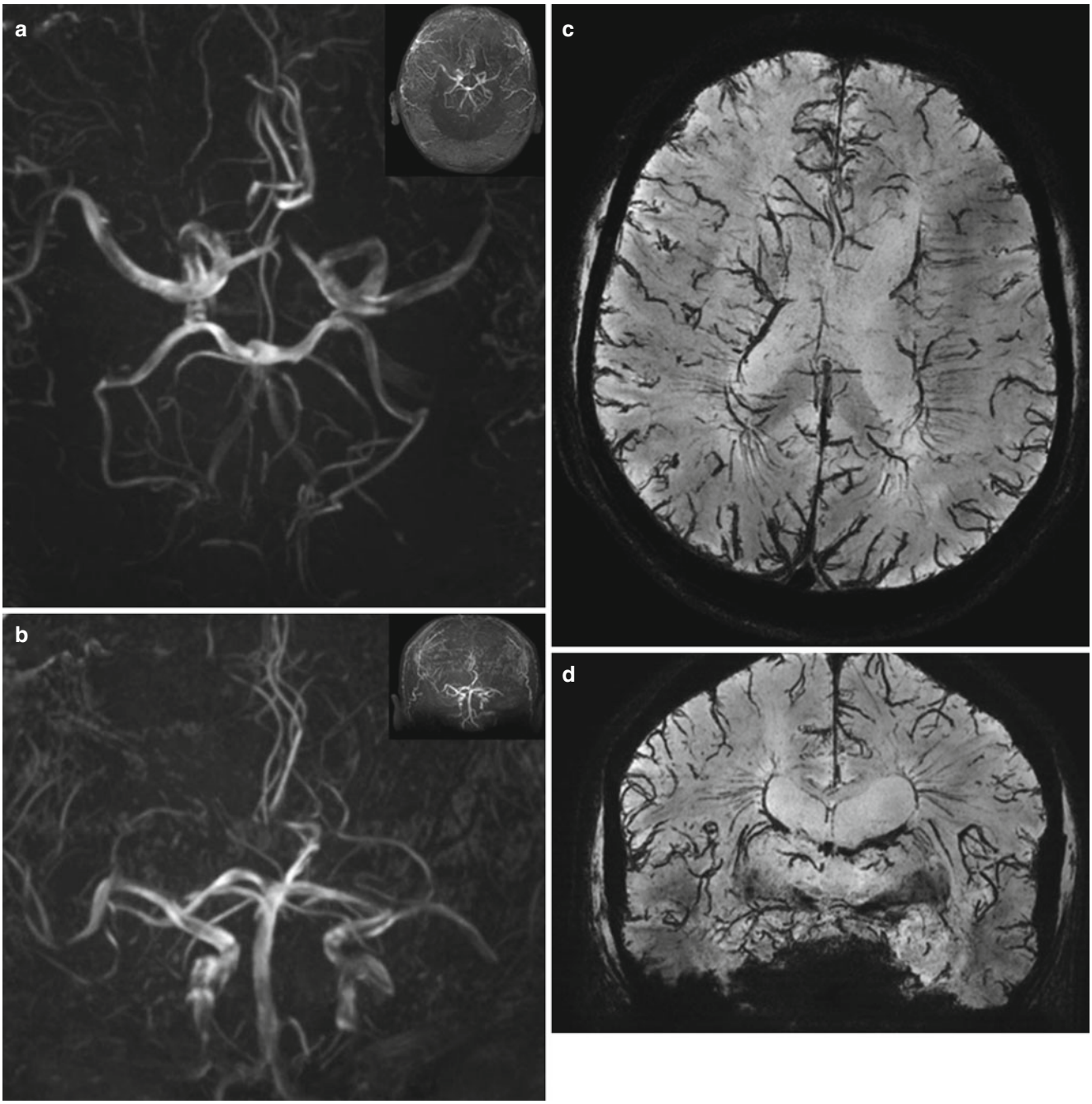

Fig. 1 Cerebral blood vessels. Dual echo susceptibility weighted imaging (SWI) of a 75-year-old healthy male (voxel sizes $0.4 \times 0.5 \times 0.6$ mm^3) showing both the cerebral arteries and veins. Depicted are a transverse and coronal first echo 3D time-of-flight (TOF) arteriogram (**a**, **b**) and a transverse and coronal second echo T2* venogram (**c**, **d**)

controls) than for 3 T imaging (33 % of early AD patients had CMBs, compared to 17 % of controls) [3] (Fig. 3). This study demonstrated that CMB prevalence in patients and controls, as counted on 7 T MRI, was much higher than reported in the literature, suggesting that MRI at regular field strength may detect only the tip of the iceberg when it comes to CMBs.

Where CMIs escape detection by conventional MRI, they appear to be within the detection limit of 7 T MRI. In Fig. 3 an example is given of a FLAIR image with small cortical hyperintensities, which represent minute acute ischemic lesions. Preliminary findings from our group now indicate that it is also possible to detect CMIs beyond the acute stage, using 7 T MRI.

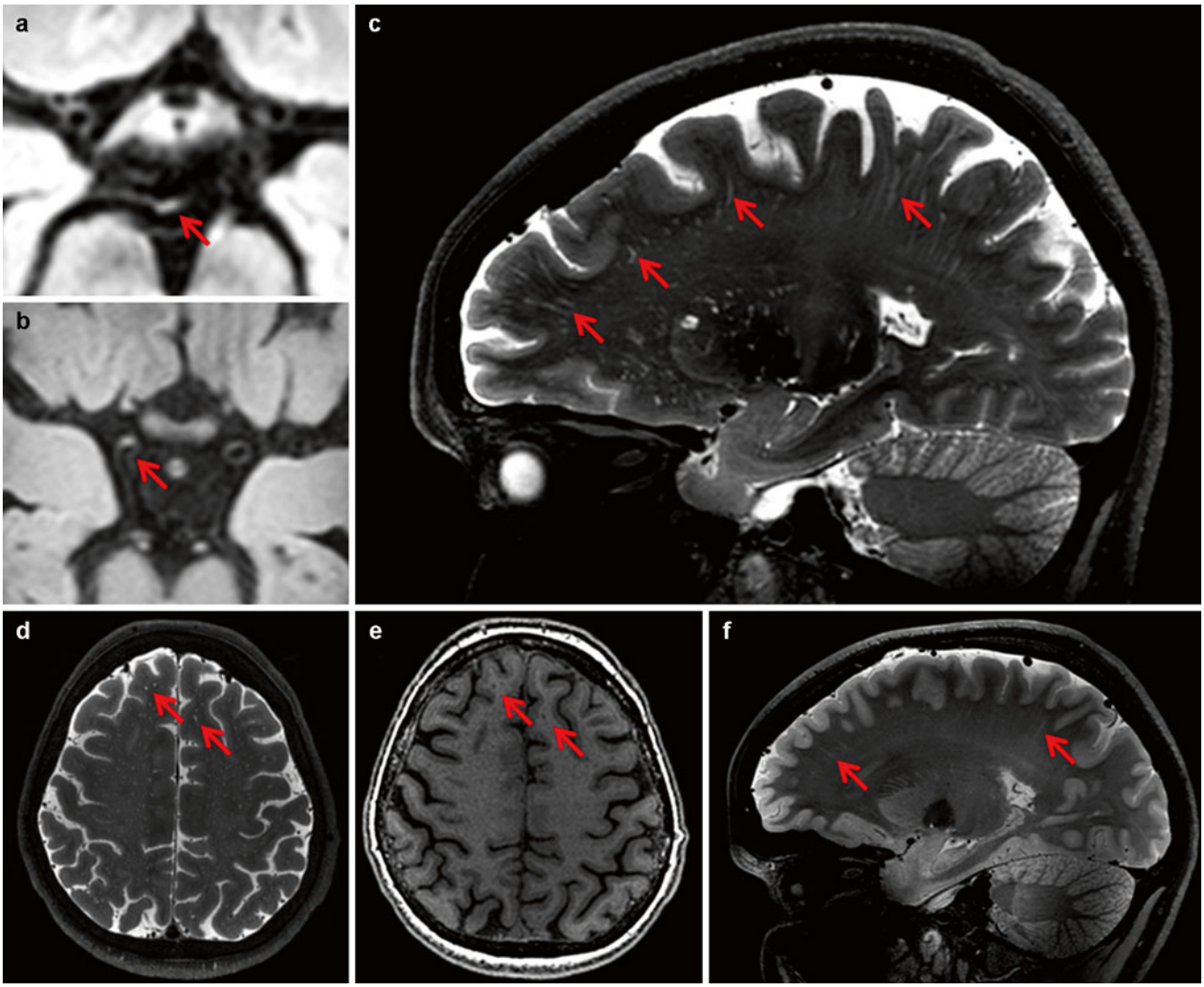

Fig. 2 Vessel walls and perivascular spaces. Transverse 3D MPIR-TSE images (voxel sizes $0.8\times0.8\times0.8$ mm^3) of a 58-year-old male with *amaurosis fugax* based on thrombo-embolism, with a focal hyperintense lesion in the basilar artery (**a**, *arrow*) and of a 49-year-old male with multiple transient ischemic attacks based on intracranial atherosclerosis, with a focal hyperintense lesion in the distal ICA (**b**, *arrow*). Sagittal T2 weighted (voxel sizes $0.8\times0.8\times0.8$ mm^3) image of a 66-year-old female shows numerous perivascular spaces throughout the brain (**c**, *arrows*). Enlarged perivascular spaces (*arrows*) in the same subject on a transverse T2 (D) and T1 weighted (voxel sizes $1.0\times1.0\times1.0$ mm^3) image (**e**, *arrows*). On a sagittal T2 weighted image of a 19-year-old male several perivascular spaces are visible (**f**, *arrows*)

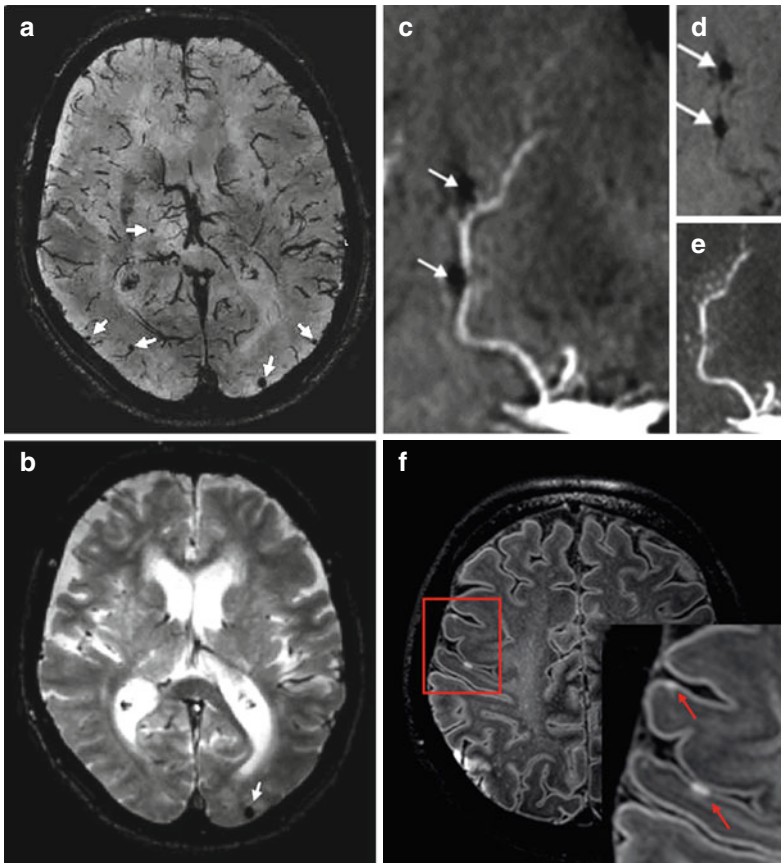

Fig. 3 Microvascular brain lesions. A minimum intensity projection of a T2* weighted image (second echo) of an 89-year old female with mild cognitive impairment shows several microbleeds in one slice (**a**). For comparison the 3T T2* weighted image of the same subject is shown, where only one microbleed is visible (**b**). A combination of a coronal minimum (**d**) and maximum (**e**) intensity projection generated from time-of-flight (*TOF*) angiography images reveals a direct correlation between microbleeds (which are, at 7T, even visible at the short *TE* used in *TOF*) and a penetrating artery in a 42-year old male (**c**). A fluid-attenuated inversion recovery (*FLAIR*) image from a 57-year old female with a history of atrial fibrillation who presented with aphasia and left-sided hemiparesis based on cortical ischemia in the right middle cerebral artery territory show small cortical hyperintensities (*arrows*), which represent minute acute ischemic lesions (**f**, *box indicates enlarged inset*)

Conclusion

The introduction of 7 T MR imaging has led to promising new directions for studying SVD *in vivo*. Pilot studies, as reviewed herein, show the potential of this technique. It is expected that within the next few years, many further studies using 7 T MRI will emerge, involving larger cohorts of patients, linking high resolution MR findings to cognitive functioning, conventional MRI measures and other relevant variables of brain health and disease. Based on such studies, the actual diagnostic, etiologic, and prognostic value of high field strength MRI for SVD will need to be established.

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